Lunar Outpost Design

3D printing regolith as a construction technique
for environmental shielding on the moon

2015 'The Design of a Lunar Outpost'
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In 2009 the European Space Agency awarded a General Study Programme contract entitled '3D printing building blocks for lunar habitation' to an industrial consortium comprised of Foster + Partners, Alta SpA, Monolite Ltd, and Scuola Superiore Sant'Anna. The main objective of the study was to investigate whether 3D printing of moon dust is a viable construction technology for possible future lunar colonisation. Each of the companies within the consortium brought their unique expertise and specialism. The research was led by Alta Spa, a space engineering company. Foster + Partners provided the overall design concepts, computational modelling and visualisations. The Perceptual Robotics laboratory (PERCRO) of the Scuola Superiore Sant'Anna provided the know-how for control systems and robotics and Monolite UK delivered the printing technology.

Ever since the Apollo missions in the late sixties, the idea of colonising the moon, or at least having a permanent base on the moon, has been the focus of many research projects. Most of these focus on very particular technical aspects of lunar colonisation and habitation.[1] This project does this to a certain extent, although it also tries to bring a more holistic approach to the design of a lunar base.

The research can broadly be divided into two main aspects. The first is mainly related to the technical feasibility of 3D printing with moon dust (or its scientific name: regolith) in a lunar environment. The chemical and physical characteristics of lunar regolith and terrestrial regolith simulant will be examined and assessed to see if it is a viable construction material for large-scale 3D printing. The second aspect of the research, and also the focus of this paper, looks at how printed structures could be used as shielding and how this could be integrated within the overall design of a lunar outpost.

A permanent base on the moon would require constructions to house and shelter astronauts and all their equipment, as well as provisions from the harsh lunar conditions. The moon is by far one of the most extreme environmental conditions one could imagine. Astronauts would have to be protected from extreme temperature differences, meteorite impacts, radiation and space vacuum.

PRECEDENTS

Over the last 40 years, most of the designs for lunar bases have been based on ready-to-use modules, which are typically transported from earth fully constructed and kitted out.[2] These modules have geometries that are compatible with launch vehicles and are often shaped to fully utilise the cargo space of launch vehicles. This is why the design of moon bases is often built around assemblies of cylindrical elements not so dissimilar to, for example, the ISS (International Space Station) modules.[3]

The problem with this approach is that the cost per square metre is extremely high. As a result, some studies have assessed lunar habitation based on inflatable structures. The advantage of inflatable structures is that they are extremely light and are highly collapsible for transportation to the moon. Some space habitation proposals, such as Bigelow[4], which was based on the TransHab[5] system, have combined core cylindrical modules with an inflatable module around the core. This hybrid approach exploits advantages provided by both systems.

Neither inflatable nor readymade modules provide adequate long term protection from the harsh lunar environment. There have been numerous studies into the shielding of permanent lunar bases[6]. One possible solution would be to use bulk material such as moon dust. There is an abundance of this material, as the moon's surface is covered with a layer, varying in thickness[7] from 20cm up to 10m. There are quite a few ways in which this bulk regolith can be applied to a structure: piling of loose regolith, retention walls and regolith sandbags[8]. Most of these concepts rely on an underlying rigid structure, such as a standard cylinder ready-to-use module.

The question is of course how this loose material can be consolidated into a usable structure. There are extremely high costs related to bringing any equipment to the moon, let alone heavy traditional construction equipment. Any feasible construction method should therefore not include large machinery. On a conceptual level, 3D printing as a construction technology could be a possible fabrication strategy, as material is only added locally and incrementally in small amounts. So there is no huge displacement of materials, requiring large and heavy machinery.

LARGE-SCALE 3D PRINTING

The consortium's expertise in 3D printing comes from Enrico Dini. He developed the D-shape printing technology, which is one of only a handful of technologies that are currently able to 3D print on the scale of buildings or building components. The D-shape technology works in a quite similar way to most additive manufacturing processes. It starts by putting down a thin (5mm) layer of fine granulates. A gantry controlled depositioning head then moves across the surface and selectively adds an inorganic binder to the sand. 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. Part of the research project is to see if the D-shape process is a feasible technology for lunar printing on a pure chemical and environmental level. Does the process work in $\frac{1}{6}$th of the earth's gravity, in vacuum and under extreme temperatures?

DESIGN OF THE BASE

The architecture of Foster + Partners is always attuned to local environmental conditions. The difference in designing on the moon is that the environmental conditions are much more extreme and complex than on earth. Therefore a set of environmental and technical requirements were established by Alta to provide the design team at Foster + Partners with guidelines for designing in a lunar environment.

One of the first ideas was to decouple the sealing capability from the thermal, mechanical and radiation protection functions. The main sealed and pressurised habitable space is, in this design, constructed from a mixture of hard shell ready-to-use modules and an inflatable structure (Fig. 1). The current design proposes an assembly of three inflatable volumes, interconnected with ready-to-use cylindrical elements that also form air locks to the outside environment (Fig. 2). The inflatables would have a typical height of 5m in order to contain two levels.

Fig. 1:

Fig. 2:

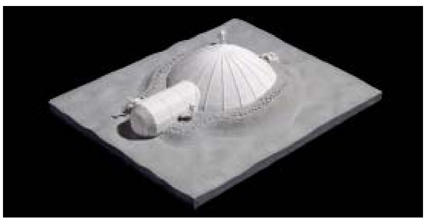
Fig. 3:

Fig. 3:

Fig. 4b:

Fig. 4c:

Fig. 4d:



The overall sectional dimension could be in the region of 10m by 5m. The overall shape of the inflatable has continuous curvature so that it can withstand the internal pressures. This inflatable does not give any protection, besides providing an atmospheric pressure and conditioned space. It is quite obvious that such a fragile structure would have very limited rigidity and will need to be protected.

This protection will come from a dome shaped shell, constructed from 3D printed regolith. The current D-shape printing process, like most 3D printers, uses a gantry system that is always of an order larger than the printed object. This is not, of course, a feasible set up for any large scale structure. We assume that to be able to print on the moon, a much more 'bottom up' approach must be taken. Smaller robots could deposit small amounts of regolith and selectively solidify them with a printing device (Fig. 3).

The D-printing process uses, just as all powder based 3D printing processes, its own powder as support structure. The problem with this approach for large-scale structures, is that in this case the dome would need to be excavated and hollowed out after it has been 3D printed. Therefore we envisioned an additional inflatable structure that would serve as a support on which the dome can be constructed. This inflatable support dome exists out of a high pressurised rib structure, on which a set of robotic printers can start to deposit layers of regolith and subsequently solidify them (Fig. 4 a-f). At the end of this process, the inflatable support dome can be removed and a second inflatable dome can be raised. This provides the low pressurised and conditioned dome in which the astronauts would live and work. In between this dome and the regolith is a vacuum cavity, which acts as an excellent insulator. This is necessary as the temperature differences on the regolith dome could potentially be as much as 200°C[9].

3D printed regolith, like masonry, has a very low tensile strength[10]. The geometry of the structure ensures that forces are primarily compression. Therefore a catenary structure was chosen to span the internal pressurised volume. In this way, mainly compression forces will be acting on the structure. (Fig. 4)

The moon has almost no atmosphere, therefore meteorites impact the surface at speeds close to 18 km/s - to put this into perspective, a bullet leaves a rifle at about 2 km/s. Although large meteorites are rather rare, a sufficient protection layer for micro-meteorite impacts is necessary. With a probability of 0.998 to have no fatal event during a lifetime of 10 years, a protection layer of 800mm is needed. This protection is achieved by offsetting the catenary structure radially by 800mm. This offset is radial as meteorites can impact the surface under any angle. (Fig. 5)

Due to the non-existence of atmosphere and magnetic fields on the moon, space radiation on the surface is far higher than on earth. There are three types of radiation that reach the moon's surface: solar wind, solar flares and galactic cosmic rays (GCR). Solar radiation will, in particular during solar flares, be the main design driver[11].

The proposed location for the lunar base is on the edge of the Shackleton Crater near the South Pole. This is one of the 'peaks of eternal sunlight', as the sun would never set and would be continuously on the horizon[12] (Fig. 6). A lunar day last 28 earth days; this means that the sun relatively rotates around the lunar base in 28 days. Therefore, any solar radiation will come in at a very low, almost horizontal angle. The geometry, and in this case the catenary curve, can be horizontally offset by 1500mm to effectively protect against solar radiation (Fig. 7).

The proposed design synthesises the main design drivers: inflatable inhabitation module, catenary structure, radial protection against meteorites and protection from radiation. The resulting structure has a variable thickness over its cross-section. It has a greater thickness at the rim, where it meets the horizontal ground plane, and is thinner at the zenith (Fig. 8).

The current D-shape printing technology uses two inorganic binders (metallic oxide and magnesium chloride) which potentially cannot be found on the moon. One of the challenges taken up by the designers is to create structures that use the minimum amount of binder per volume of regolith, seeking to optimise the overall regolith protection skin, without losing its overall rigidity

Fig. 4e:

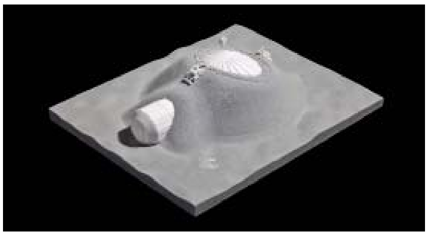


Fig. 4f:

Fig. 5:

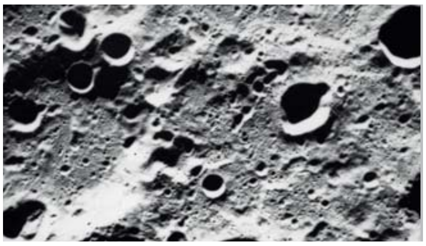


Fig. 6:

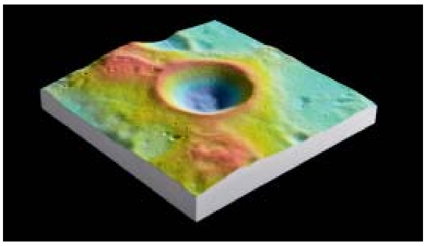
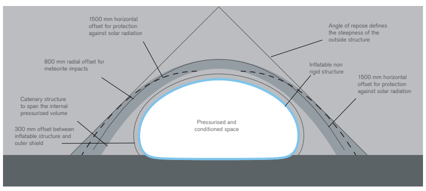


Fig. 7:

Fig. 8:



INTERNAL STRUCTURES

One of the lightest space filling topological systems that can be found in nature are foam structures. Foams are often defined as a two-phase system, in which typically a high volume of gas cells are enclosed in a liquid or solid state. In this case we have loose regolith enclosed in a 3D printed closed wall cell system.

There are two main reasons why a closed wall foam system was chosen. Firstly, although the thickness of the regolith would protect from meteorites, it does not minimise the damage from such an impact. To absorb the impact of meteorites, a layered approach of solidified and loose regolith would be ideal to disperse the energy of the impact.

Secondly, closed foams also have the advantage that any section through the structure delivers a structural platform. This is crucial as the regolith dome will be built up from horizontal layers. Each of these layers will need to be a platform from where the 3D printing robots need to build the next layer.

A parametric model and script were developed by the Specialist Modelling Group at Foster + Partners to investigate the usability of foam as internal structure of the regolith shield (Fig. 9). A structural feasibility study has been pursued, making some simplifying assumptions, by performing a structural analysis on a shell structure, a comparative Finite Elements (FE) structural analysis on small samples with different cell sizes and an analytical study comparing the cell structure with other materials [13].

To verify the D-shape printing process two different demonstrators were produced. The first one was a 1.3 ton and 1.5 metre long section of the regolith dome printed at D-shape (Fig. 10 – 11) . The second demonstrator was a much smaller sample and aimed to test the printing process in a vacuum. A small test rig was created with a printing nozzle that injected the binder a few millimetres beneath the top of the regolith simulant. This was to avoid immediate evaporation of the binder liquid in a vacuum. This test resulted in six small spherical 3D printed pieces, which demonstrated the feasibility of 3D printing in vacuum (Fig. 12 – 13).

Many more years of research would of course be needed before we send the first robotic 3D printers to the moon. But it does show the potential for using 3D printed regolith as a construction methodology for shielding on the moon, and suggests how this could be integrated in an overall design strategy for future moon bases (Fig. 14).

Fig. 9:

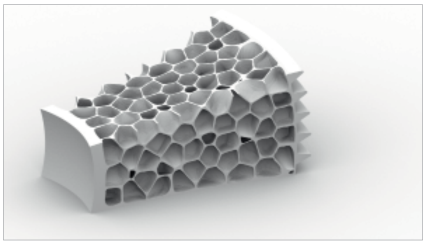


Fig. 10:

Fig. 11:

Fig. 12:

Fig. 13:

Fig. 14:

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