IAC-18.E5.1. x47746

USING SOLAR SINTERING TO BUILD INFRASTRUCTURE ON THE MOON LATEST ADVANCEMENTS IN THE REGOLIGHT PROJECT

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Abstract
In-Situ-Resource Utilisation (ISRU) will be needed if humans want to sustain their presence on extra-terrestrial bodies for extended periods of time. In the past years, a renewed focus has been put on ISRU concepts, specifically in the context of Additive Layer Manufacturing or 3D printing to be able to create necessary radiation shielding for habitats and shelters. Different approaches to use the regolith of the Mars or the moon for building radiation shielded pressurized habitats, unpressurized shelters or for modelling the terrain have been investigated. Project RegoLight progresses solar sintering from a Technology Readiness Level (TRL) 3 to 5 as an alternative Additive Manufacturing (AM) to microwave sintering, contour crafting and others. Solar sintering has the advantage that no binders are needed, building elements such as interlocking bricks can be sintered with only using the sun and the sand thus reducing the material which needs to be brought from earth. The project RegoLight has been funded through the European Commission and comprises five partners: DLR in Cologne (coordinator), Space Applications Services (Belgium), COMEX (France), LIQUIFER Systems Group (Austria) and Bollinger + Grohmann Ingenieure (Austria). The project started in November 2016 and ended in June 2018. This paper provides the conclusions of project RegoLight with regard to the projects' main objectives:

- AM approach for automated fabrication of building elements under ambient conditions,
- Automated fabrication of larger structures through a mobile printing head in ambient conditions
- Demonstration of producing a `building element' block from lunar regolith simulant by applying the solar sintering AM approach using a solar furnace automated setup under vacuum conditions.
- Production of a `building element' with a fine structure (resolution 1.4 cm) from lunar regolith simulant under ambient conditions
- Design and validation of interlocking building elements, providing a modular system for a variety of space architecture and mission requirements,
- Characterization of the building elements produced (materials metrology)
- Study of the application of solar sintering element manufacturing in the larger frame of a lunar base architecture (e.g. Moon Village)

Latest RegoLight developments also include the description of the next steps to further the technology and mature the outcomes. The RegoLight project demonstrates the viability of solar sintering for establishing a lunar base and other necessary infrastructure made from in-situ-resources.

Keywords: Lunar Base, additive manufacturing, solar sintering, tests in ambient and vacuum conditions, automated fabrication, interlocking building elements

Acronyms/Abbreviations
Additive Manufacturing (AM), Technology Readiness Level (TRL), In Situ Resources Utilization (ISRU)

1. Introduction

The RegoLight project investigated the sintering process of lunar regolith simulants by means of concentrated sunlight in order to prepare for future lunar missions for building infrastructure (leveled terrain, dust shelters, launch pads etc.) and structural components for lunar habitats. RegoLight aimed at enhancing a specific additive layer manufacturing technique – which seems very promising for lunar applications since it does not involve any consumables – by further characterizing the parameters for sintering different types of regolith and by developing a movable printing head capable both of pointing the concentrated solar beam at the required spot and of deploying incrementally additional layers of regolith in order to continue with the additive building process. Based on the mechanical properties of solar sintered regolith, architectural scenarios and applications were developed, taking into account the benefits of additive layer manufacturing and novel construction concepts for lunar gravity. A detailed Finite Element Modeling provided first insight into lunar architectural applications using this technology. With a concurrent engineering approach sample structures were printed having been derived from "big picture" scenarios and bottom up approaches at the same time. The project objective was the development of a regolith solar sintering device breadboard which was validated in a relevant environment (vacuum TRL5). The printed parts underwent mechanical properties tests to build a database and FEM analysis for validation of the concepts.

The paper is a more detailed and full description of the work done as part of project RegoLight. First insights were published in the paper titled "Advancing Solar Sintering for Building A Base On The Moon" published in the IAC 2017 proceedings (Imhof et.al., 2017).

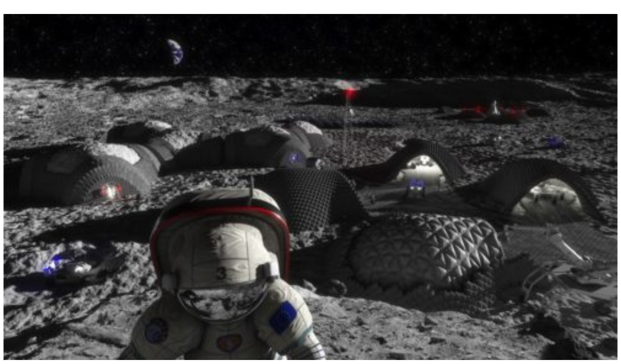

Fig. 1: Conceptual view of an operational lunar base showing habitat, hangar and operational pads, credit: RegoLight consortium, visualization: LIQUIFER Systems Group, 2018.

2. RegoLight approach and methods

The project was developed through three different printing campaign raising the TRL level from 3 – experimental proof of concept to nearly 5 – technology validated in relevant environment (Vacuum 3D printing campaign). Further the team adopted a concurrent engineering approach looking from the detail, a granular matter perspective to developing the automated 3D printers and to a larger perspective in describing the context, the scenarios and possible implementation options for a lunar base. Scenarios and applications were extensively studied and contextualised within current international mission plans.

Section 3 describes the research work and is followed by an overview of the main results. Which geometries were applied in the different printing campaigns are detailed in Section 5. The structural engineering provided feed-back for the development of the geometries – see Section 6. How the research can fit into a lunar base scenario is described thereafter followed by Sections about the results and a concluding paragraph.

3. Description of research

The verification of the TRL advancement took place through solar sintering samples in three different printing campaigns. The lunar soil simulant used in all 3D printing campaigns was JSC-2A.

3.1 <u>3D Printing & Fabrication of basic building elements</u>

All the samples were produced as part of the 3D printing campaign displayed in Section 3.2.1 *Solar sintering in ambient conditions* in a laboratory environment.

The first step was to concentrate the solar light to the maximum achievable in order to obtain a resolution <10 mm for sintering. The focal point could not be smaller than 14 mm: a more concentrated light led to the break of the mirror. In practice, since the sintering cannot always occur at the exact focal point, the sintering resolution is about 20-30mm.

3.1.1 <u>*Half-sphere and triangle*</u>

The sintering speed was around 1 layer/minute with the regolith passing under the beam at a speed of 48mm/sec. The feeding took around 10 seconds.

Support materials made of alumina and zirconia were used as substrate for the first layers. The porosity and the high temperature resistance were ideal to prevent the warping of the sintered parts.

Figure ***2:*** shows a solar 3D printed triangle and half sphere. The triangle was successfully 3D printed but the sintering resolution and feeding were not accurate enough for the half-sphere.

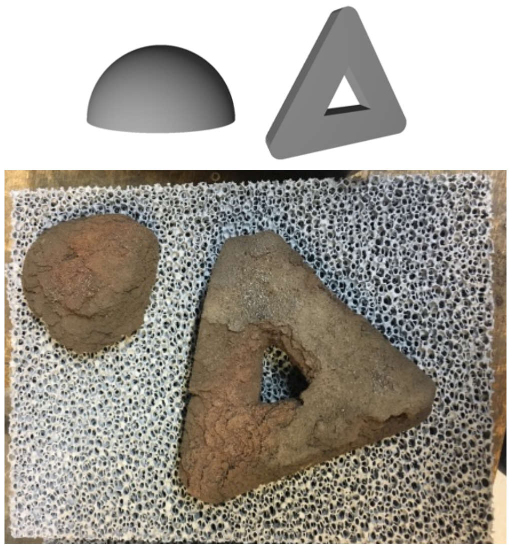

Figure 2: Computer designed half-sphere and triangle (top) and actual solar 3D printed parts (bottom). Support size 21 cm x 30 cm, credit: RegoLight consortium, photo: DLR

3.1.2 Complex shape

Figure 3: shows the sintering trial of a complex shape. The quality of the feeding was not high enough to sinter the shape properly. Irregular delamination and warping of the part was preventing a sufficient outcome of the 3D printing.

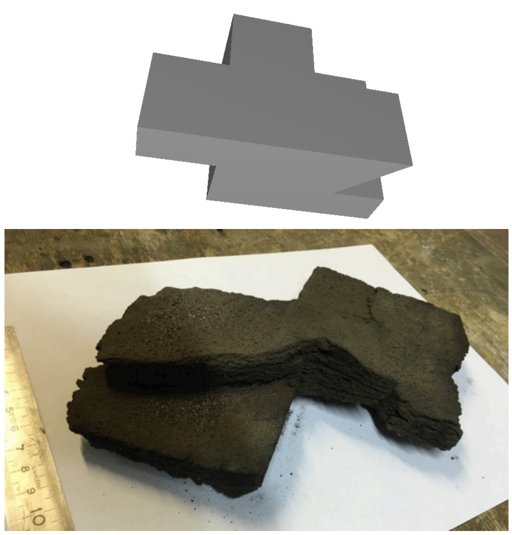

Figure 3: Computer designed complex object (top) and actual sintered part (bottom), credit: RegoLight consortium, photo: DLR

3.1.3 Interlocking building element

After the sintering of basic geometries, actual interlocking building elements were solar sintered. Figure 4**:** shows the actual 3D printed element. Some features of the building element were not printed. The resolution of the concentrated Xenon light beam and the feeding quality led to a building element with rounded edges. More trials, with various printing paths led to the same results.

Figure 4: Computer designed interlocking building element (top) and actual sintered part (bottom), credit: RegoLight consortium, photo: DLR

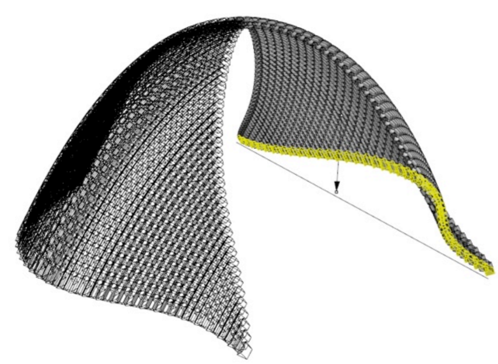

Fig. 5: Dome constructed from elements in Figure 4: with the centre of mass such that no scaffolding is needed, credit: RegoLight consortium, visualization: LIQUIFER Systems Group

3.1.4 Other elements

Another interlocking element was designed to prove the concept of the interlocking capability of solar sintered parts. A T-shape was manufactured with the solar 3D printing process and the part could be tightly interlocked with a sintered S-shaped element, see Figure 6**:** .

Figure 6: Solar 3D printed T-shape (top) interlocked in the S-shape (bottom), credit: RegoLight consortium, photo: DLR.

3.2 <u>Printing Campaigns</u>

In the following the printing campaigns which led subsequently to a raise of the TRL level from 3 to 5 are being described.

3.2.1 <u>Solar sintering in ambient conditions in a laboratory environment</u>

For the first solar sintering experiment, an automated set-up was designed and constructed. It comprised of a feeder and its control system and a solar sintering 3-axis table. Everything was successfully integrated with the systems available at DLR, specifically the Xenon lights which provided the sun simulation and the computer interfaces. For solar sintering campaign was scheduled for two weeks to operate and to deliver a variety of sintered elements ranging from basic geometries to complex interlocking parts. Geometries could be fed through special programmed software directly to the printer.

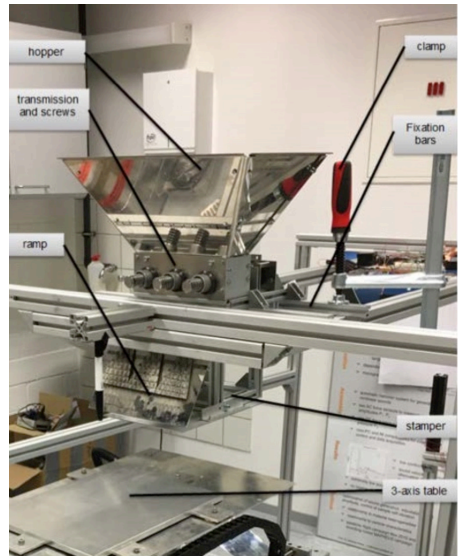

Figure 7: 3-axis table setup with feeder and control system in the DLR laboratory, credit: RegoLight consortium, photo: Space Applications Services.

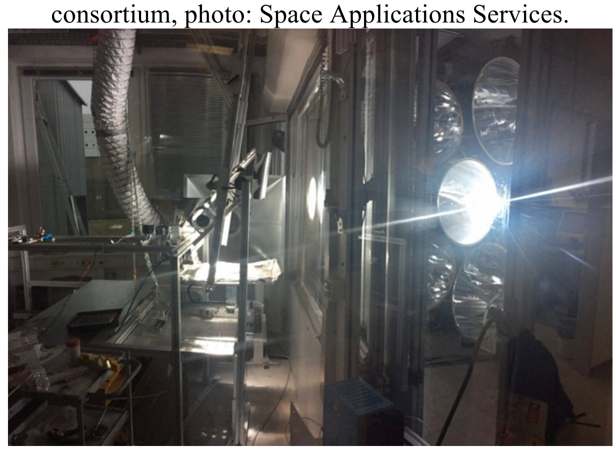

Figure 8: Solar sintering campaign in operational state, credit: RegoLight consortium, photo: LIQUIFER Systems Group

3.2.2 <u>Solar sintering in ambient conditions in an exterior environment with a mobile printing head</u>

The mobile solar sinter device was set-up such that it could be transferred on a future lunar mission into an assembly installed on a large gantry-like lunar rover. In this setup, the solar sintering installation was outside using the solar beams and a mobile Fresnel lens which concentrated the solar light while the printing table fixed – see Figure 9. The layering of the regolith simulant came from a feeder system, slightly less elaborated than the one used for the tests in the laboratory environment. Also in these tests the geometries could be fed through specifically developed software – same directly to the printer.

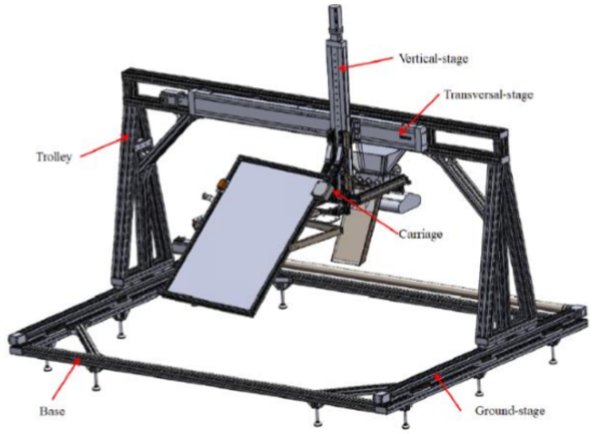

Figure 9: Mobile printing head as implemented, credit: RegoLight consortium, photo: Space Applications Services

3.2.3 Solar sintering in a vacuum chamber in a relevant environment advancing to TRL 5

The vacuum-rated system was implemented using practical engineering design practices. Parts were selected based on outgassing criteria. Vacuum rated lubrication was applied on the gears in order to avoid potential cold welding (although unlikely given the vacuum levels to be used).

Given the impossibility of procuring a new chamber as, a small, existing chamber already available was used. The use of a small chamber presented challenges for the printer design: it required a complete redesign of the system (as described in 3.1.1), only a small hopper could be used and only very small parts could be printed. It was neither possible to use spreaders to improve material distribution nor possible to test stamping. The confined space implied that the thermal protection covers could interfere with the printing process, since they required more freedom in order to move without touching the piece.

Nevertheless, a system compliant with the requirements was implemented (depicted below).

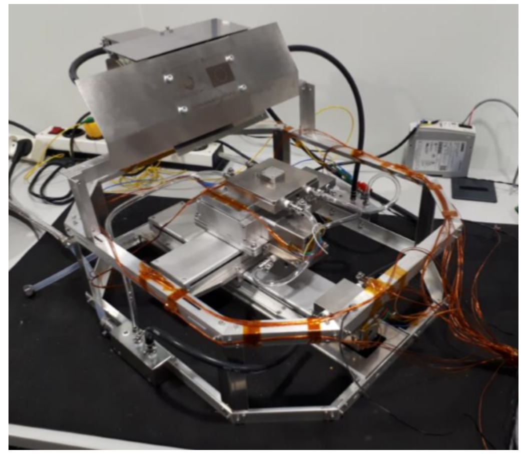

Fig. 10: Completed setup for the vacuum experiment (thermal covers not shown), credit: RegoLight consortium, photo: Space Applications Services

Initial solar sintering under vacuum was conducted in order to study the risks before the actual 3D printing. Based on this, JSC-2A simulant was placed on top of a fire brick and mounted in the vacuum chamber. The chamber was evacuated up to approximately 150 mbar for 30 minutes and the concentrated solar beam was held at one spot for a duration of 8 seconds. Results from the thermal camera showed that the temperature raise above the 1200℃ which is the melting temperature of applied regolith simulant.

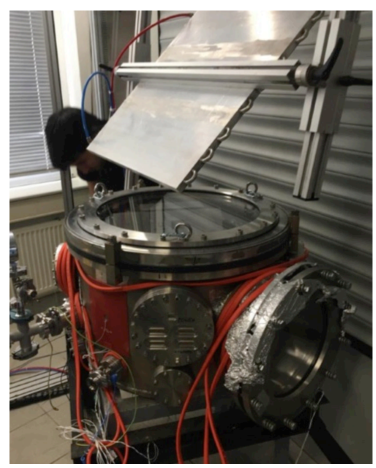

Figure 11: The chamber with the 3D printer installed under the solar furnace mirror, credit: RegoLight consortium, photo: DLR

4. Results from the printing campaigns

4.1.1 Results from the solar sintering in ambient conditions in a laboratory environment

Objects with the same 2D cross-sections could be solar 3D printed with focused Xenon lights and the feeding hardware. The resolution of the beam and the feeding were however not sufficient for the sintering of more complex parts. The solar sintering of the designed interlocking building element was partially successful as some features could not be 3D printed and the overall material integrity was not very strong.

Compressions and bending test measurements were performed on cut solar sintered regolith. Compression test samples had to be covered by a thin layer of concrete in order to compress the sample over flat surfaces. As for the bending tests, the samples produced from the small bricks were 10 x 10 x 40 ± 5 mm and tested parallel to the layers plan. The large brick provided larger samples, 10 x 20 x 70 ± 5 mm that were tested perpendicularly to the layer plan. Figure **12** shows a typical sample prepared for compression tests and Figure 13: typical samples for bending test.

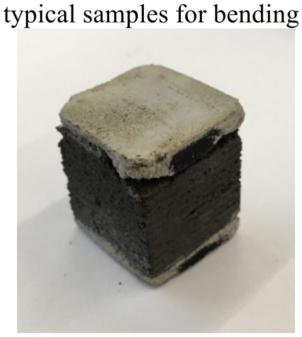

Figure 12: One 20 mm x 20 mm x 20 mm of sintered lunar regolith covered with gypsum - typical compression test sample, credit: RegoLight consortium, photo: DLR

Figure 13: Samples 10 mm x 10 mm x 40 mm (top) and 10 mm x 20 mm x 70 mm (bottom) for bending tests, credit: RegoLight consortium, photo: DLR

4.1.2 *Results from the solar sintering in ambient conditions in an exterior environment with a mobile printing head*

The results of the sintering tests called for a redesign of the interlocking brick elements. This resulted in the geometry below where the wavy surface of the element ensures sufficient resistance to transverse shear when the elements form the surface of e.g. a shell structure. Finite Element analysis was used to evaluate the designs.

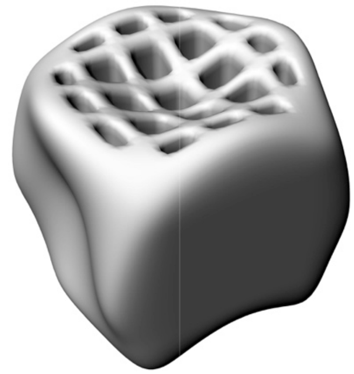

Fig. 14: Interlocking brick element with wavy surface, credit: RegoLight consortium, photo: LIQUIFER Systems Group 2017

Parameter studies with regards to maximum headroom and cross section height were performed on compression arches using the load-cases dead weight and moon quake. The aim was to derive the structural height of the interlocking bricks so that the stresses in the material lie inside the bounds given by the derived design strength values.

Figure 15: Printed Specimen, credit: RegoLight consortium, photo: Space Applications Services

4.1.3 *Results from the solar sintering in a vacuum chamber in a relevant environment*

It could be shown that it is possible to solar sinter with the devices as set up but the element was disintegrated and thus a full TRL 5 could not be reached.

5. Applications

The team developed different categories of interlocking building elements to meet the various requirements of the RegoLight applications and solar sintering campaigns. For the three printing campaigns three different interlocking elements were selected and further iterated to overcome the constraints of the tests see Figure **16** and Figure **17**.

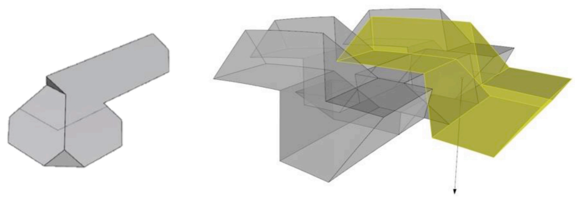

Figure 16: Tetrahedron geometry selected for the Ambient printing campaign, credit: RegoLight consortium, visualisation: LIQUIFER Systems Group

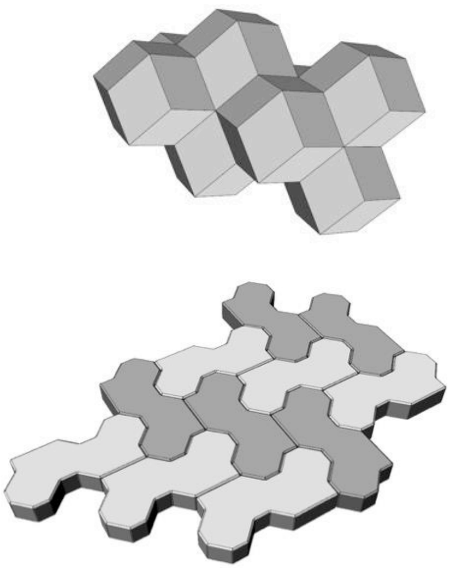

Figure 17: Top: Rhombic Dodecahedron selected for the mobile printing campaign. Bottom: Surface battlement structure selected for vacuum printing campaign, credit: RegoLight consortium, visualisation: LIQUIFER Systems Group 2017

Another research path focussed on topological interlocking assemblies and elements. It also displays specific characteristics that interlocking elements should have in a lunar environment. Following different approaches in parallel, a variety of element types were developed:

- Elements with 3-dimensional interlocking capacities; e.g. 3D formfitting stackable (e.g. derived from Platonic geometries, comb-shaped), 3D randomly packed aggregates
- Elements with 2.5-dimensional interlocking capacities, e.g. formfitting for curved and self-supporting vault construction elements
    - Elements with 2-dimensional interlocking capacities, e.g. flat ground stabilizing elements for surface battlement

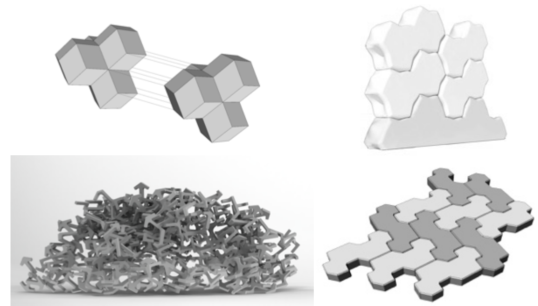

Figure 18: Geometries of interlocking building elements for 3D formfitting stackable top left, 2.5-dimensional elements top right, 3D randomly packed aggregates bottom left, 2-dimensional interlocking elements bottom right, credit: RegoLight consortium, visualisation: LIQUIFER Systems Group

A catalogue of nearly 40 different variations summarized all the developed interlocking elements.

For the ambient printing campaign, the tetrahedron geometry (see Figure **16**) belonging to the “Elements with 2.5-dimensional interlocking” capacities group was selected. Based on the results and lessons learnt from the ambient printing campaign a Rhombic Dodecahedron (top visualisation of Figure **17**.) belonging to the Elements with 3-dimensional interlocking capacities group was selected for the mobile printing campaign. This particular element was also used for the development of the complete lunar base habitat envelope as displayed in Figure 19 and Figure **20**.

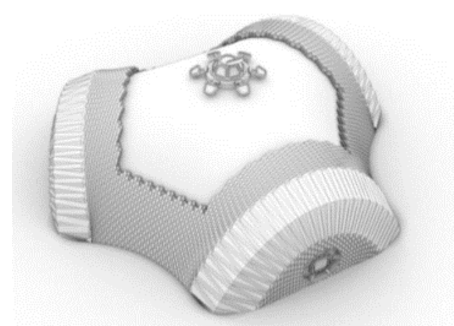

Figure 19: Lunar habitat with protection shield made up of RegoLight interlocking elements, credit: RegoLight consortium, visualisation: LIQUIFER Systems Group, 2018

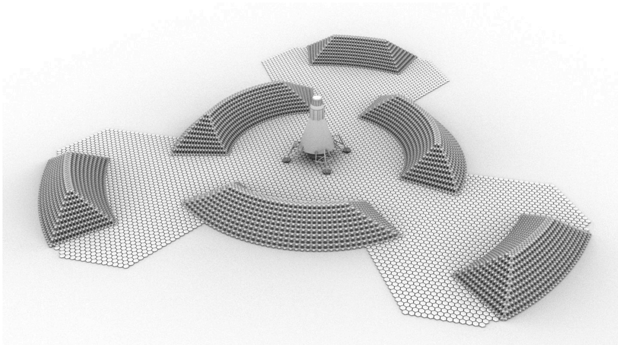

Figure 20: Launch pad with dust protection shield and flat terrain made made up of RegoLight interlocking elements, credit: RegoLight consortium, visualisation: LIQUIFER Systems Group, 2018

Due to the volume constraint of the final vacuum printing campaign a simpler surface battlement type interlocking element was chosen (bottom visualisation of Figure **17**.).

6. Structural typology and building principles

In the course of the printing campaigns it turned out, that the printer resolution of 2cm is currently not sufficient to print the described brick elements in Figure **16** with sufficient accuracy when using brick elements with realistic dimensions.

Therefore, alternative interlocking brick geometries were developed which took account of the limited printer resolution. Therefore, brick geometries with wafy surfaces, interlocking brick elements based on Dodecahedrons were selected for further investigation. Figure 21 shows how larger units can be formed from individual cells. Within the larger units, tensile stresses can be transmitted as long as their amplitude stays below the tensile strength of the sintered material. Due to their geometry, the elements interlock with their neighbours and thus form larger load-bearing units.

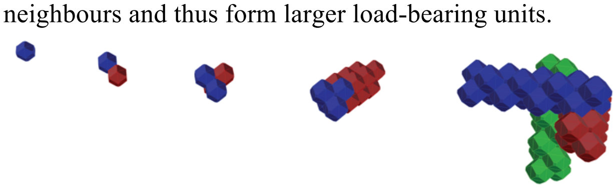

Figure 21: Assembly of larger brick units based on dodecahedral cells, credit: RegoLight consortium, visualisation: Bollinger Grohmann, 2018

Several options of units of Dodecahedral cells for use as structural elements were investigated. The most promising results were attained with bricks consisting of four Dodecahedrons. Figure 22 shows how these bricks were idealized as equivalent beam structures.

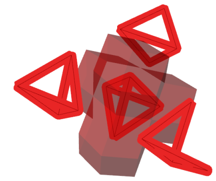

Figure 22: Idealization of tetrahedral brick units using tetrahedral beam cells, credit: RegoLight consortium, visualisation: Bollinger Grohmann, 2018

Each brick is reduced to a Tetrahedron whose edges (red lines in the above image) are modelled as beam elements. The corners of the Tetrahedron lie at the centres of the Dodecahedral cells and the beam elements model the internal connectivity. These beams can carry tensile load in the range allowed by the tensile strength of the sintered material. The connection between the bricks is via contact only. This means that only compressive stresses can be exchanged between the cell units. The image below shows how these contact conditions were modelled using beam elements which are oriented perpendicularly to the inter-brick contact surfaces:

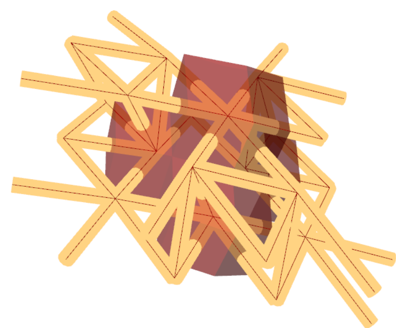

Figure 23: Idealization of contact conditions between the tetrahedral brick elements using beams using compression-only conditions, credit: RegoLight consortium, visualisation: Bollinger Grohmann, 2018

For the numerical analysis of structures made up of such brick elements a non-linear approach was utilized, where contact elements which transmit tensile forces are gradually removed from the model in an iterative procedure. This takes account of the possibility that individual contact zones may open due to the action of external loads without endangering the overall structural stability.

Since sintered Regolith has a much larger resistance to compressive than to tensile stresses, geometries for shelters were developed with predominantly compressive forces. The basis for these were hanging membrane simulations: when a flexible, initially flat membrane which spans between the support lines of the intended shell structure, is loaded by its dead weight a deflected shape results which is predominantly under tension. The amplitude of the deflected can be controlled by scaling the deadweight by a factor. When the deflected shape is turned upside down the internal forces change sign and a structure with mostly compressive stresses results.

The image below shows one of the shapes derived based on the above described form finding method.

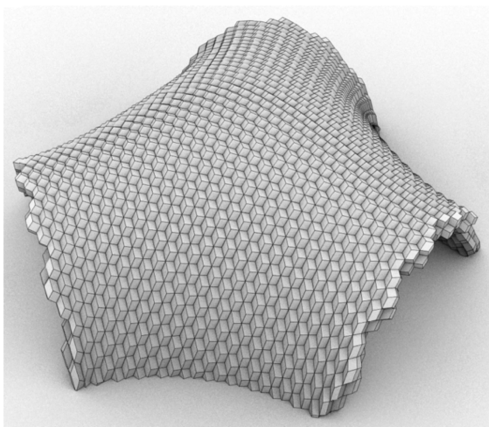

Figure 24: Shape derived from hanging model for compression only stress state under deadweight; credit: RegoLight consortium, visualization: LIQUIFER Systems Group, 2017

Based on this geometry a structural model based on beam elements was generated. The image below shows the beam geometry, the applied support conditions and loads. At the footings, all translational movements are blocked, at the openings no movements perpendicular to the plane of the openings are allowed since it is assumed that these form planes of symmetry to neighbouring structures.

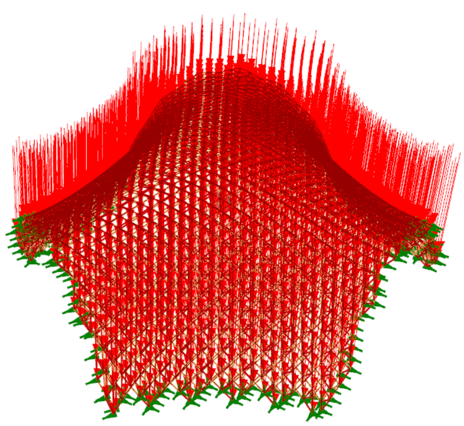

Figure 25: Finite Element model consisting of beam elements with loads and support conditions, credit: RegoLight consortium, visualisation: Bollinger Grohmann, 2018

Using the non-linear procedure where contact elements with tension forces get gradually removed from the structure a distribution of normal forces like in the image below results. The blue rectangles mean the corresponding normal forces in the contact elements are under compression. This proves that the structure stands up under the given loads without the necessity of tensile connections between the interlocking brick elements.

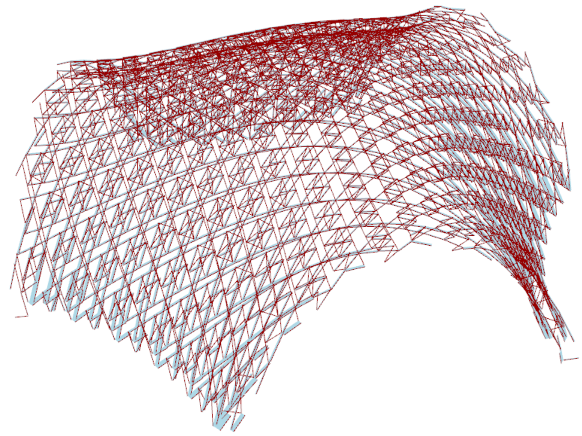

Figure 26: Compressive normal forces in final structure with contact elements under tension removed. The stability of the remaining structure proves the viability of assembling structures from element with compression-only connections., credit: RegoLight consortium, visualisation: Bollinger Grohmann, 2018

7. Scenarios for a lunar base

One objective was to develop specific scenarios for solar sintering applications and infrastructure elements which could be solar sintered. The work methodology was 'concurrent engineering' where all partners worked from the detail to the big picture and the other way around at the same time influencing each other's work. The work carried out in this task referenced the Global Exploration Roadmap, Lunar Surface Missions, Human and Robotic Surface Activities, definition of mission architecture elements /building types and state-of-the-Art of Additive Manufacturing (AM) of habitats.

The main topics which were investigated were the following:

- Mission architecture and functional elements considerations (contextualization of the manufacturing technique and the machinery needed for building mission architecture elements / application scenarios)
- Baseline scenario concepts (four baseline concepts using multi-purpose robots were investigated)
- Mission scenario that refers to the sintering and building processes

Figure 27 depicts a lunar base with all necessary elements and shows how a building robots and processes could take place.

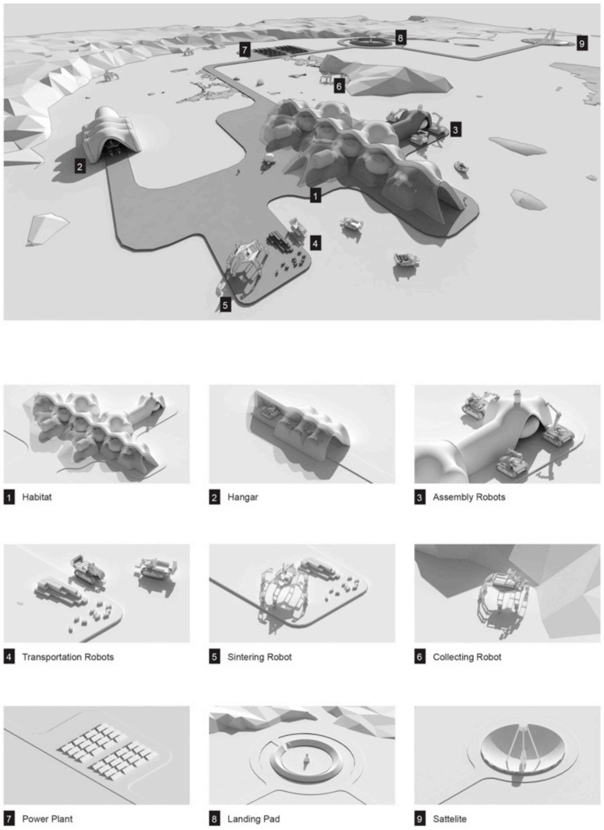

Figure 27: RegoLight scenario, credit: RegoLight consortium, visualization: LIQUIFER Systems Group, 2017

8. Results and recommendations

The outcome of the printing campaigns showed that elements could be sintered with a resolution of 14 mm with a sintering speed of 1 layer/minute, more specifically regolith passing under the beam at a speed of 48mm/sec. with a layer feeding every 10 seconds at its fastest speed. The mechanical properties which could be sintered were close to those of gypsum but are expected to become similar to non-reinforced standard concrete.

The recommendations are important when going into a next phase of technology development creating a solid TRL 5 in sintering an integrated regolith simulant element. To achieve this, the delamination of the single sintered layers needs to be improved through optimizing temperature and layer thickness as well as even distribution of regolith per layer. The geometry of the interlocking elements is recommended to be with beveled or obtuse-angles. Elements shall be within the given constraints as big as possible to shorten assembly process and to minimize geometric tolerance failures. Further it is advantageous to have a survey process in parallel to the building process to ensure right placement of the elements. Generally speaking, it needs to be noted that designs shall look for a compact geometry such as the space filler geometry and the larger the interlocking elements are the less important is the resolution. The overall envelope geometry shall be such that large tensile forces should be avoided since the sintered elements can only withstand pressure forces.

9. Conclusions

The currently ongoing planning and solicitation of funds for a continuation of RegoLight is targeting the improvement of the mechanical quality of the printed items on several fronts: The biggest challenge is still the size of available vacuum chambers in the world, where a solution to bringing a mobile Xenon-lamp setup to Marseilles is being outlined. The materials physics of 3D printing is a very broad topic and is being considered on many levels including computer simulation and additional projects at the various partners of RegoLight and otherwise. These efforts are naturally of a slower pace, since they are scientifically more fundamental in nature.

RegoLight has demonstrated several unique technical achievements and has overcome many challenges already. In addition, the project has also identified the biggest challenges for a planned future project. Hence, a continuation is likely addressing the remaining gaps which shall be the priority of a future consolidation effort.

Acknowledgements
The project has received funding from the European Horizon 2020 Programme, within the topic of COMPET-03-2015 under the grant agreement number 686202.

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