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Advancing Solar Sintering for Building A Base On The Moon

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Abstract
In the last few years, different concepts have been investigated in the context of building human-tended bases in extra-terrestrial environments through ISRU. NASA has conducted a 3D printed habitat challenge in 2015, which put international focus on the topic. Amongst microwave sintering, contour crafting and other Additive Manufacturing (AM) technologies using local resources on extra-terrestrial bodies, solar sintering has been the least investigated. In this context, the project RegoLight, sintering lunar regolith with solar light, is currently being developed..

The project has been funded through the European Commission to advance the Technology Readiness Level (TRL) from 3 to 5 and comprises five partners. Under the lead of the DLR in Cologne, Space Applications Services (Belgium), COMEX (France), LIQUIFER Systems Group (Austria) and Bollinger + Grohmann Ingenieure (Austria) collaborate to advance solar sintering technology in preparation of infrastructure construction on the moon. The project started in November 2016 and will terminate end of April 2018. This paper provides an overview of project RegoLight with regard to the projects' main objectives:

- Utilization of the AM approach for automated fabrication of building elements. A regolith simulant feeder is used in a solar furnace, under ambient conditions.
- Automated fabrication of larger structures through a mobile printing head outside the solar furnace and 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 without bonding agent, using a solar light source under ambient conditions.
- Design and validation of an interlocking building element, which when combined could be used for a variety of space architecture and mission requirements in a modular fashion
- Characterization of the building elements produced (materials metrology)
- Study the application of solar sintering element manufacturing in the frame of the larger picture of a lunar base architecture; also by considering concepts such as the ESA "Moon Village"

The ultimate goal of the project is to help pave the way for future long duration, sustainable, crewed exploration to the moon. Projects such as RegoLight use local resources to create ecological solutions using only lunar sand and the sun to build protective shelters for humans.

Keywords: soil sintering, automated fabrication, interlocking building elements, moon base

Nomenclature

µm	Micrometer
MPa	MegaPascal
GPa	GigaPascal
JSC-2A	describes a lunar soil simulant of the mares
kW	kilo Watt
kW/m²	kilo Watt per square metre
mm/s	millimetre per second
$MgCl_2$	Mangane Chlorid
MgO	Mangane Oxid

Acronyms/Abbreviations

AM	Additive (Layer) Manufacturing
ESA	European Space Agency
COTS	Commercial of the shelf
FEMA	Feeder Electro-Mechanical Assembly
FPCU	Feeder Power and Control Unit
DG	Director General
DLR	German Aerospace Centre
NCGU	Numerical Control Generation Unit
SLM	Selective Laser Melting
TEMA	Table Electro-Mechanical Assembly
TRL	Technology Readiness Level

1 Introduction

The project RegoLight is timely in view of major commercial space industries' current call for moon bases. Apart from the ESA DG Jan Wörner and his vision for a lunar village, Elon Musk, founder of Space X, has expressed his interest in establishing a lunar outpost within the next 50 years [1].

The paper describes the ongoing project RegoLight, a 2.5-year project terminating at the end of April 2018. RegoLight investigates the possibility of solar sintering lunar regolith into meaningful interlocking building elements. These elements can be used to build habitation envelopes to protect humans from radiation and for living for extended periods of time on the moon. Ideally, using only in-situ resources, the sun and sand, sintering printers can produce interlocking bricks and lay them into a habitation envelope.

Solar sintering is defined as "a technology that is particularly useful for crafting objects and at the large scale, structures, in dry environments using only sunlight and sand or regolith (rock dust)"[2]. The sintering process involves fine grains of metallic or ceramic material which get heated below melting temperature into a solid material. For this process, microwaves and concentrated sunlight, amongst other heat sources, can be used.

The paper displays how the project RegoLight develops technologies for the solar sintering of lunar soil simulant and increases knowledge beyond the State-of-the-Art, explained in section 2. In section 3, the research problem is stated and in section 4 solutions are addressed. Section 5 describes similar work that has been done or is under way, in related research fields internationally, followed by preliminary results in (6) and conclusions in (7).

2 Beyond the State-Of-the-Art

Solar sintering of regolith is currently at TRL3 and demonstrates the ability to build a 'brick' composed of sintered regolith; manufactured in a laboratory set-up comprised of a mechanical table able to move the raw material (regolith) in the x, y and z axis. The regolith set in action is sintered, taking shape layer by layer as it passes through a concentrated solar beam, powered by a solar furnace. Project RegoLight is projected to raise the TRL level from 3 to 5 through developing a regolith solar sintering device breadboard to be validated in a relevant environment (vacuum).

RegoLight has advanced the state-of-the-art, by applying the AM approach to the solar sintering process, allowing for automated fabrication of building elements in a solar furnace. As a final step, RegoLight will demonstrate, for the first time, the solar sintering of lunar regolith in a lunar analogue environment (vacuum chamber. This printing campaign is planned for September 2017 hence no reports can be incorporated into the paper.

The RegoLight project includes a integrated approach in deriving the actual shape of elements to be printed based on the simultaneous development of mission scenarios.

1. *Concurrent Engineering approach is used to derive 3D applications for solar sintering*: RegoLight mission scenarios are developed based on international projections for moon base requirements to ensure that the final product (sintered element) is well placed within the larger context of international strategy and mission planning.
2. *Solar sintering of 3D samples with a fine structure:* creation of 3D sintered elements with a fine structure has never been done with the sun as energy source producing a fine structure. Combining inexhaustible energy and structural engineering advances the current state-of-the-art.
3. *Solar sintering of 3D samples using a mobile device (TRL 4):* using robotics, an automated and mobile process capable of solar sintering has been built. (already achieved)
4. *Solar Sintering of 3D samples in a vacuum chamber (TRL 5):* managing a solar sintering process in an environment close to the lunar one will be a major advancement of the TRL level, beyond the actual state-of-the-art. This has never been done before.
5. *Structural standards for building on the moon:* extending the structural standards for building on the moon: reviewing the preliminary standards which have been derived for Lunar construction and extending them; taking into account structural engineering implications, 3D printing technologies and solar sintering processes.

3 Problem statement

The body of the moon is surrounded by a vacuum, and is therefore exposed to solar radiation and occasional solar particle events. This poses extreme danger to the health of a crew and also to sensitive equipment. Further, the upper layer of the lunar body consists of very fine and abrasive dust which due to the $1/6^{th}$ gravity takes longer to settle than on earth once it is whirled up by either a landing or launching vehicle. Since this dust can destroy mechanical interfaces and easily penetrate space suits, dust contamination needs to be limited as much as possible. On the other hand, due to the lack of an atmosphere, the moon is exposed to an abundance of sunlight.

Solar sintering is a way of minimising the transport of resources from earth because material found locally on the moon can be utilized for building habitation. Using the sun's energy and in-situ lunar sand, paved pathways, radiation protection, launch aprons and levelled terrain for a radio telescope can be manufactured. Therefore, it is vital to push the TRL of solar sintering so that it can contribute to sustainable future exploration missions to the moon.

4 Description of research

RegoLight is developed by simultaneously addressing both large and small-scale design parameters. Thus, the project team ensures that the final geometries of the interlocking building elements will be suitable for use in constructing a habitable envelope.

In the interdisciplinary team comprising scientists, engineers and architects, material scientists select the soil simulants, study their behaviour during sintering and test the samples for their material properties. Three special sintering set-ups have been planned for this project and designed by mechanical space engineers. Firstly, an x-y-z-table with a soil simulant feeder and computer software was developed to sinter small test geometries in an ambient controlled environment using Xenon lamps simulating the lunar light. Secondly, a mobile printer with a printing volume of 500x500x1000mm has been built to test larger geometries for building elements using the sun; and thirdly, a very small printer is being developed to test solar sintering of lunar soil simulants in vacuum conditions.

The team of architects, structural and space engineers design a variety of interlocking elements which can fit the requirements of the different 3D-printer setups and a solar beam diameter ranging between 20mm and 10mm. Extensive geometric studies were undergone to develop these building elements while at the same time the larger context has been considered, too: different lunar base scenarios, their needs for radiation and dust protection, and terrain levelling through sintered material. The geometries for the interlocking building elements are being adapted in an iterative process after each sintering campaign in coordination with the material tests.

4.1. Production of a building element with a fine structure

Solar sintering parameters were defined using the experience of the ESA study "3D printing of a model building block for a lunar base outer shell". Two xenon lamps were used for keeping a concentrated light source, about 5 kW, steady over the several hours required for the completion of a 3D-printed part. The lamps were manually calibrated in order to have a concentrated solar beam as sharp as possible, and a focal point diameter of a minimum size. A 12mm diameter spot at the focal point resulted from the best calibration thus leading to a flux density at the focal point of 1200 kW/m². A water-cooled mirror was used for changing the beam orientation from horizontal to vertical. At the focal point, a porous ceramic plate was mounted on a programmable 3-axis table. A regolith feeding system was synchronized with a 3-axis table for having coordinated motions of both elements. The AM process consisted in, first, dropping off a thin layer of JSC-2A lunar regolith simulant, approximately 100 µm thick, on top of the ceramic plate. Then the 3-axis table would move the ceramic plate covered with regolith under the concentrated solar beam following a predefined computer-programmed pattern at 48 mm/s for sintering the deposited material. Once a layer sintered, the feeding system dropped off a new layer of simulant and the sintering could start again. The feeding and sintering steps were repeated for two to three hours for building up 3D objects. Between the sintering of two layers, a water-cooled shutter was closed for preventing the incoming solar beam from being reflected on the mirror and damaging the hardware in a feeding position.

Figure 1 shows the developed setup

used for the AM of lunar regolith using concentrated light.

Basic test geometries, brick shape, were successfully sintered for the realization of mechanical tests, described further.

Figure 1: Experimental setup at DLR-Cologne Solar simulator. The Xenon lamps are placed behind the water-cooled metallic shutter (right hand side behind the glass). credit: RegoLight, photo: LIQUIFER Systems Group 2017

4.2 Solar sinter printer developments

RegoLight partner Space Applications Services was responsible for the hardware and software prototypes of three printers; an Ambient 3D printer, a Vacuum 3D printer and a Mobile 3D printer.

4.2.1 Ambient 3D printing System

The Ambient system comprises three components: the Numerical Control Generation Unit (NCGU), hardware and software which process a 3D model provided by the habitat design specialists, by generating instructions for the printer to make the part out of regolith simulant; the Feeder Electro-Mechanical Assembly (FEMA), which holds and conveys the material to the surface to be printed; and the Feeder Power and Control Unit (FPCU), which commands the FEMA in order to push the material into the surface.

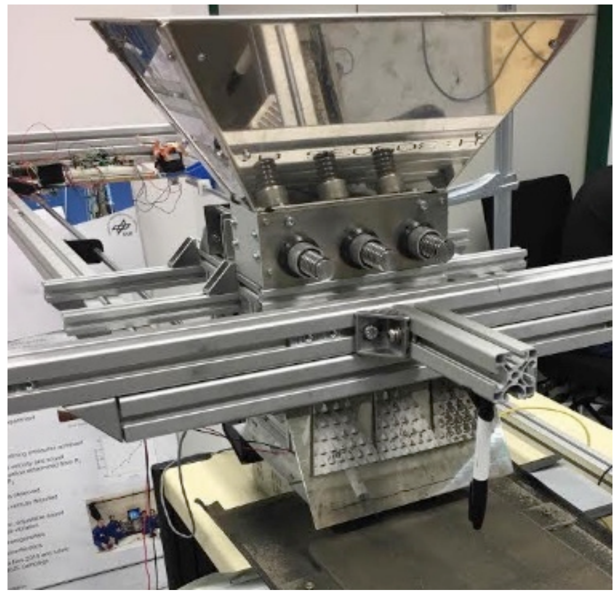

Figure 2 - Feeder Electro Mechanical Assembly (FEMA) of the Ambient 3D printer System, credit: RegoLight, photo: Space Applications Services, 2017

The 3-axis Table Electro-Mechanical Assembly (TEMA) consists of a COTS 3-axis table operating in conjunction with said systems (NCGU, FEMA, FPCU), and is able to move a tray, or testbed, with the accumulating layers of regolith under the sintering light beam. The TEMA also moves the tray under the feeder in between layers for the feeding process to take place. The ambient 3D printing system operates in conjunction with the solar simulator at DLR.

4.2.2 Vacuum System

The vacuum system is similar to the ambient 3D printing system, with the additional requirement of being compatible with a vacuum chamber already present at DLR.

The modifications include a reduction in capacity of the hopper, and the disposition and geometry of the auger conveyors. Particular adaptations have been made for the mechanisms to be compatible with the vacuum and thermal environment, and the likely additional dust accumulation in an enclosed space. The vacuum system also operates with the solar simulator at DLR.

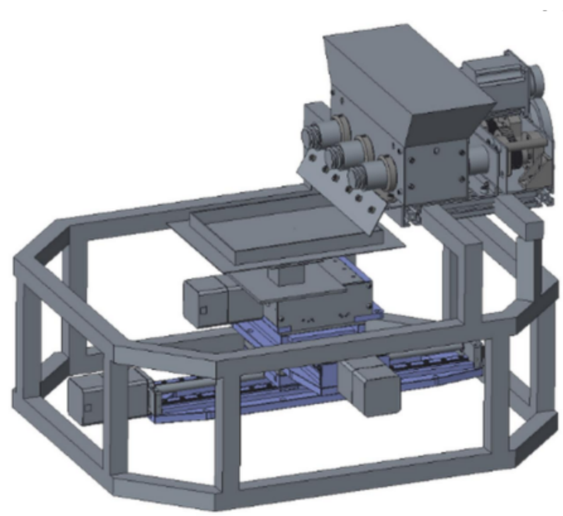

Figure 3 – Vacuum 3D Printer System, credit: RegoLight Consortium, visualization: Space Applications Services, 2017

4.2.3 Mobile System

The ground-based RegoLight Mobile System is a system analogous to one that could be used one day on the moon surface and aims at demonstrating printing operations in an operational setting closer to the real one.

The system is represented as a lightweight lens that is oriented in a 3-dimensional space, in such a way that the focal point of the lens is always located at the desired point of sintering, while the point of sintering is moved layer-wise, and with the added ability of depositing a new layer of feedstock, and consequently repeating the process.

The system reuses several of the subsystems developed for the other 3D printers in the project, namely the feeder (FEMA) and software components in the NCGU. However, the key difference between this system and the others developed within the RegoLight project is the capability of moving the lens, as opposed to the sintering bed, thus allowing the construction of larger building blocks than those that can be moved with an XYZ table, as well as removing the need for the infrastructure of a large solar simulator.

Figure 4 - Mobile 3D Printer System, credit: RegoLight Consortium, photo: LIQUIFER Systems Group, 2017

4.2.4 PyRegolight Software

A Python-based software was progressively developed and enhanced during the project in order to operate the three different 3D printers. The aim of the software is to control the Ambient and Vacuum TEMAs or the Mobile System gantry i.e. to move the different axes simultaneously to perform the trajectories and make the sintering on the regolith surface. In the case of the mobile system, the software takes into account the sun position in the sky and illumination to alter the sintering speed and pause the process when there is cloud cover (the latter only applicable to Earth-based hardware).

A feeding operation is performed after the sintering operation to provide another layer of regolith. In the case of the Ambient and Vacuum Systems, the feeder is fixed, however in the case of the Mobile System, the feeder is located on the same carriage as the lens, and can be controlled with the same program.

4.3 Characterization of sintered elements

Structures generally need to fulfill two basic requirements: they should be safe (i.e. not collapse under external loads) and be usable during their projected lifetime. Since structural geometry, material properties and external loads are subject to random variations the building industry has widely adopted the semi probabilistic safety concept to ensure that the probability of failure of any given structure lies below a pre-defined, widely accepted level. In case of most buildings this probability of failure lies at $p_f = 2 \cdot 10^{-7}$ during their lifetime. The basis of this concept forms so-called design values for external loads and material properties.

Using the specimen of sintered regolith from printing campaign I, mechanical tests were conducted to quantify the mean value and standard deviation of their strength and elastic properties (see section 6.2.). These test results served as the input for the calculation of design values according to Eurocode 0 (7):

$$X_d = \mu \cdot e^{-0.8 \cdot \beta \cdot V}$$

Here μ is the mean value of a tested material property, V its variance and β the reliability index which sets the level of safety of the resulting design value X_d.

The material tests revealed for all measured properties a large ratio of standard deviation to mean value thus resulting in rather low design values. For a probability of failure of $p_f = 10^{-5}$ the corresponding β-value is 4.27. This failure probability was deemed acceptable and was thus used in all further calculations. Another significant finding of the tests was that material properties were heavily dependent on the orientation of the sintered layers relative to main loading direction. The cause of this lies in the low ratio of inter-layer bond to in-plane material strength.

For compression perpendicular to the sintered layers a design value of

$$fcd = 0.94 kN/cm^2$$

could be reached. This amounts to a reduction of the corresponding mean value by a factor of 2.6 and lies on a level with standard concrete.

To determine the tensile bending strength of sintered regolith two test series were conducted:

a) bending parallel to sintered layers, with the vector of bending moment perpendicular to the sintered planes
b) bending perpendicular to sintered layers where the inter-layer bond transfers shear stresses

Case a) resulted in a design value of the tensile bending strength of $f_{bd} = 0.074 N/mm^2$. For case b) a design value of $f_{bd} = 0.053 N/mm^2$ could be achieved. The safety factors with regards to the corresponding mean values lie at 7.4 and 4.3 respectively. The lower strength value for case b) in comparison to case a) comes as no surprise and can be explained with the relatively poor inter-layer bond. From the safety factors, it can be seen that the inter-layer bond reduces the overall tensile bending strength but does so consistently which reduces the ratio of standard deviation to mean value.

By assuming that poor interlayer bond governs failure in case b), an approximate tensile strength of the inter-layer bond can be deduced. From the three point bending test, a maximum inter-layer shear stress of

$$\tau_{bond,max,Sd} = 1.5 \cdot \frac{V_{Sd}}{A} = 0.008 N/mm^2$$

results. Here V_{Sd} is the maximum transverse shear force and A the specimens cross section area.

Assuming zero normal stresses at the position of maximum transverse shear, it can be deduced from Mohrs circle that

$$\sigma_{bond,max,Sd} = \tau_{bond,max,Sd} = 0.008 N/mm^2$$

where $\sigma_{bond,max,Sd}$ is the tensile strength of the inter layer bond.

Like concrete, sintered regolith exhibits brittle failure under tension with a large variation of the ultimate limit loads. The above calculations show however that these tensile capacities can be reliably used in a structural context.

4.4 Design of interlocking building elements

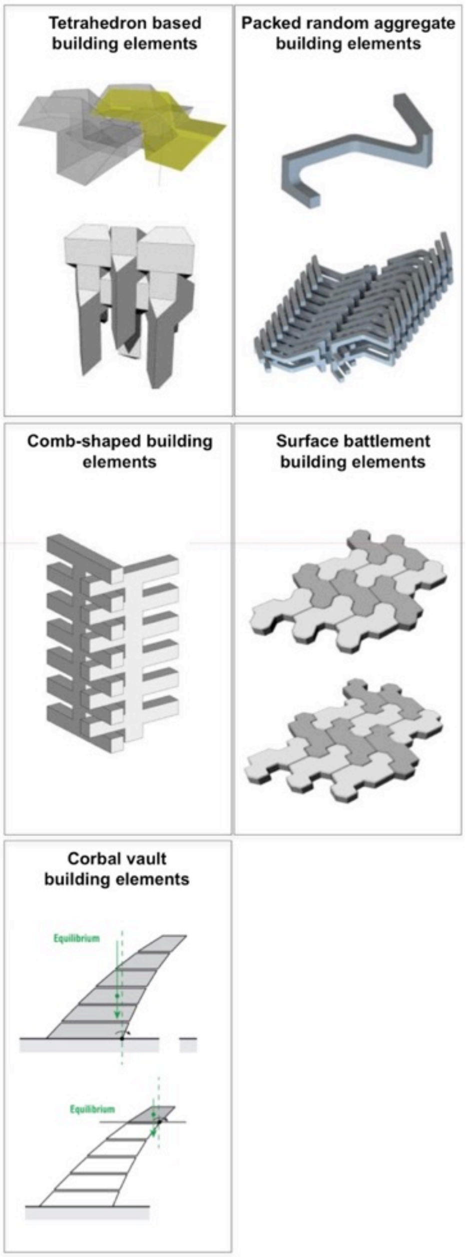

Figure 5 - different interlocking element options for various scenarios, credit: RegoLight, visualization: LIQUIFER Systems Group 2017

A range of interlocking elements was designed for the main scenarios. Firstly, a tight-fitting tetrahedron based element was explored for its self-centering quality during construction, eliminating the need for external scaffolding during construction of a moon base. (see Figure 7)

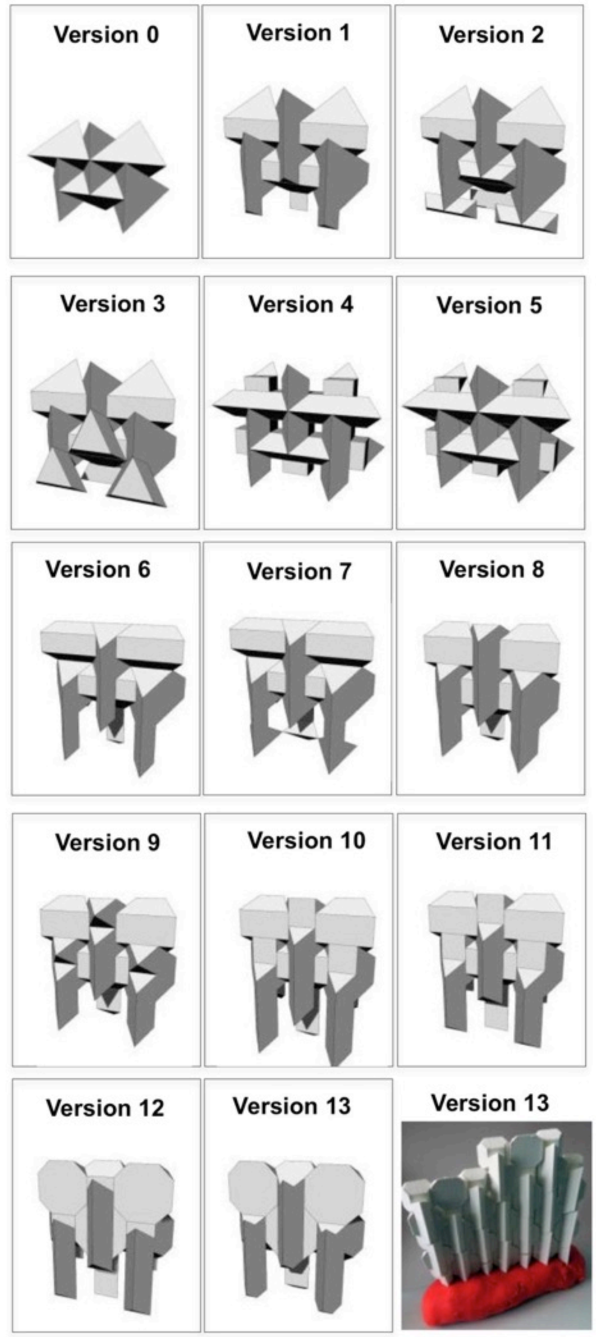

Figure 6 - Development of the tetrahedron based interlocking element with final geometry pictured in version 13, credit: RegoLight, visualization: LIQUIFER Systems Group 2017

The tetrahedron interlocking element has sharp edges and allows the construction of a completely sealed habitat envelope. The corbel vault building elements present an alternative option for habitation shells. Elements loosely piled into a packed state provide dust protection and can be used for a launch pad dust apron. These randomly packed elements can also be used as a fill layer in a 3-metre-thick habitation shell. Inbetween this loose agglomeration they could be filled with regolith thus the aggregate elements can be used as a frame for the loose regolith. Also presented as an option in Figure 5, are the comb-shaped elements which can be used for non-pressurized shelters, needing less radiation protection. Another category was surface battlement building elements, similar to those currently used in terrestrial applications.

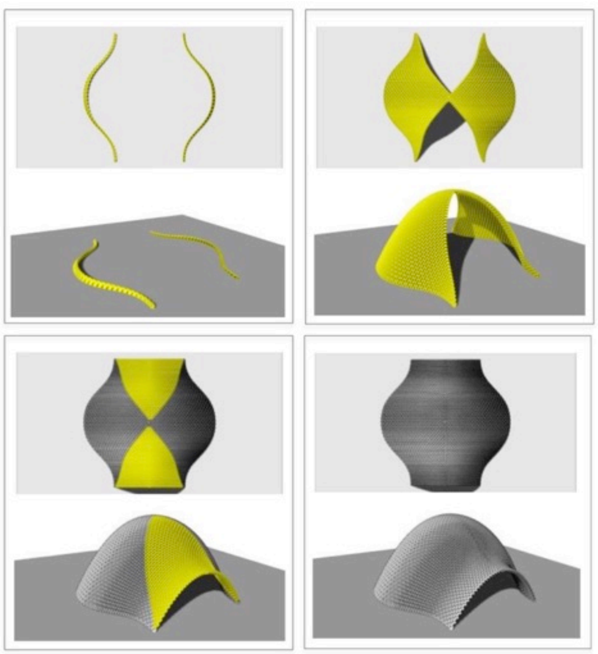

Figure 7 - Build-up of a habitat envelope using the tetrahedron element, credit: RegoLight, visualization: LIQUIFER Systems Group 2017

In Figure 6, the development and optimization of the tetrahedron interlocking building element is displayed to demonstrate the iteration process of finding a geometry that would address building requirements.

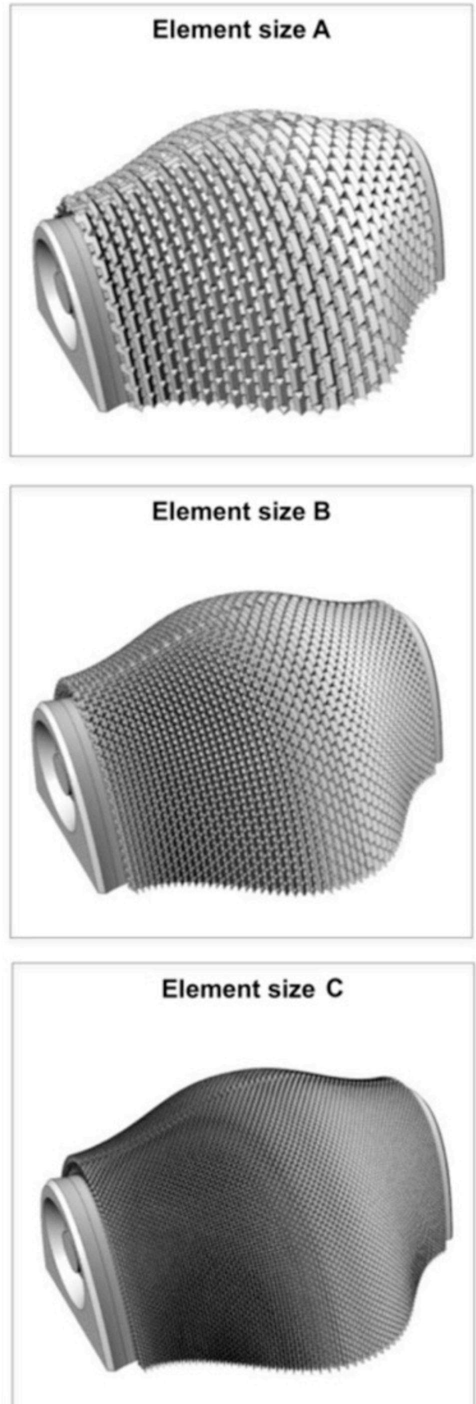

Figure 8- Options of size variations using the tetrahedron element, credit: RegoLight, visualization: LIQUIFER Systems Group 2017

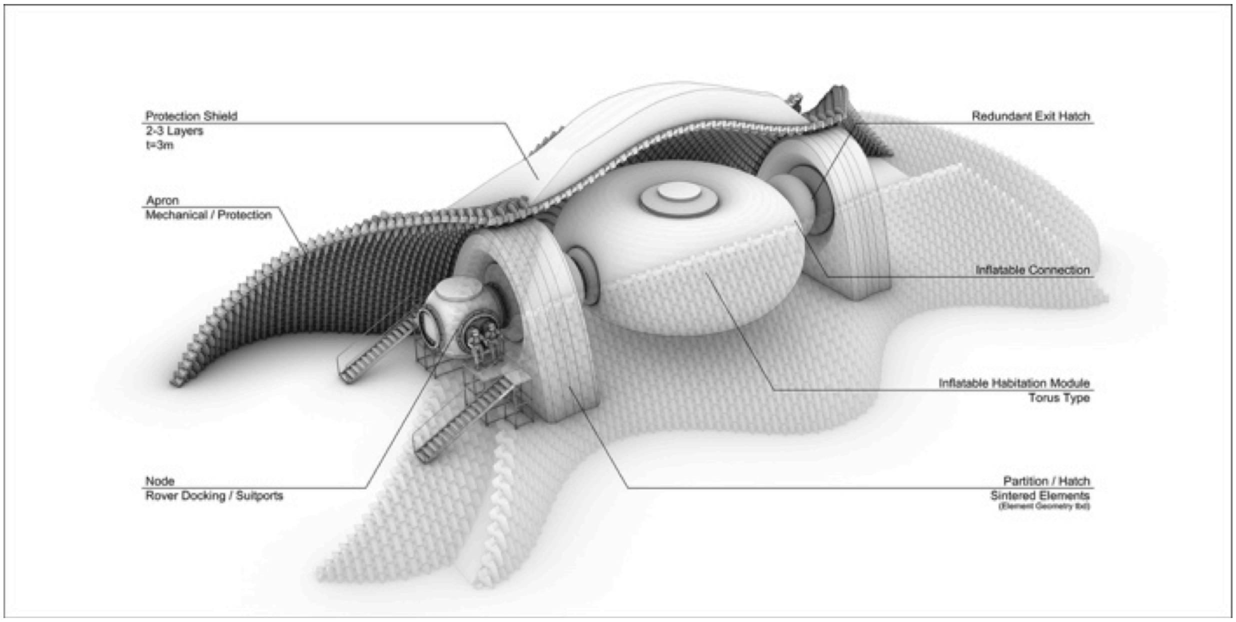

Figure 9 - Lunar habitat envelope constructed through tetrahedron elements, credit: RegoLight, visualization: LIQUIFER Systems Group 2017

Figure 7 shows how a habitat envelope using the tetrahedron shaped interlocking elements could be assembled. First, the foundation is laid in the form of two s-shaped curves. Next, the sides are built-up along the curves, until they meet each other at the top, creating a self-sustainable hull. The centre of mass for each element, and the structure as a whole as it is being assembled, is self-supporting, requiring no external building support. Once the sides are complete, the building pieces that comprise the front and back of the habitat are filled in.

Figure 8 shows the different sizes of the interlocking elements, resulting in varied appearance and function of the overall structure. Optimal element size for the different habitation types can be adapted depending on the solar sinter volume and the assembly robots..

Figure 9 shows how the interior of a such a volume can be outfitted with inflatable pressure-bearing volumes that house the habitable zones. Towards the open front and backside, a sintered regolith wall with airlocks, suitports and docking possibilities needs to be erected after the inflatable shell has been deployed to close off the opening for full radiation protection.

4.5 Application scenarios

The team identified the following applications scenarios for the solar sintered RegoLight interlocking elements:

1. Shielding against lunar environment, for pressurized and non-pressurized lunar infrastructure

- Application: Creating a bearing structure to shield against dust, micrometeorites, radiation
- Geometry: Tetrahedron and Corbel-vault

Figure 10 - Lunar base, credit: LIQUIFER Systems Group 2016

Pressure bladders. For airtight volumes, another medium (resin coated walls, inflatable rubber layers, etc.) needs to be supplied. It can also be imagined that a larger sintered protective structure can house several smaller habitats within. This can provide greater security in case of an emergency, by allowing one or two habitats to remain functional, as others need to be shut down. A layout needs to be chosen which can fulfil these requirements.

2. Building elements for non-pressurized volumes (hanger, storage units for cargo, equipment that needs protection, servicing)
- Application: These elements form the fundamental building structure to house vehicles, equipment, antennas or any other infrastructural items that do not require pressurization.
- Geometry: Tetrahedron, Corbel-vault, comb-shaped and packed random aggregate elements.

Figure 11: On left: Hanger housing a lander and NASA SEV rover. On right: Communication tower that can be built using RegoLight building elements. Credit: RegoLight consortium and NASA

3. Dust protection in terrain (e.g. launch pad apron)
- Application: Creating sloping structure to shield against dust
- Geometry: Corbel-vault and packed random aggregate elements.

Figure 12: Launch pad with shield to protect against the dust created during the landing and launch sequence of a spacecraft. Credit: RegoLight consortium

4. Terrain modelling (e.g. flat sintered terrain for roads, to level the construction site and for paving craters for installation of larger equipment, such as telescopes)
- Application: Creating a solid flat structure for vehicles to traverse or for installing scientific equipment, e.g. telescopes
- Geometry: Comb shaped or surface battlement structures.

	Architectural Element	RegoLight application scenarios
Pressurized Facility	Base Habitat	1, Terrain modelling. 2, Shielding against lunar environment.
	Recycling Plant	
	Disaster and crisis center	
	Green House	
Non- pressurized Facility	Electrical Power Supply Facility	1, Terrain modelling. 2, Construction of building structure. 3, Shielding against lunar environment.
	Power Plant	1, Terrain modelling. 2, Construction of building structure. 3, Shielding against lunar environment.
	Gas and Fuel Storage	1, Terrain modelling. 2, Construction of building structure. 3, Shielding against lunar environment.
	Thermal Control Facility	
	Storage Facility	
External Facility	Hangers	1, Terrain modelling. 2, Construction of building structure. 3, Shielding against lunar environment.
	Operational Pads	1, Terrain modelling. 2, Dust protection
	Road ways	1, Terrain modelling
	Telescope	1, Terrain modelling. 2, Construction of partial building structure. 3, Shielding against lunar environment.
	Communication Tower	1, Terrain modelling. 2, Construction of partial building structure

Table 1: RegoLight Application Scenarios

Table 1 summarizes the different lunar infrastructure elements and their related RegoLight application scenarios.

5 Related work in the international field

Closely related to RegoLight is the Lunar Habitation project developed by Foster & Partners. This ESA coordinated project [3], focused on 3D printing technology as it applies to the building of a lunar base outer shell. They adapted pre-existing, D-shape technology for a lunar application and built a 1.5ton mock-up. Their MgCl2 binding agent reacts with the MgO already present in the lunar regolith in order to create a solid structure. The feasibility of the process has been shown in a vacuum atmosphere, with a honeycomb structure as technical demonstrator. Mechanical and physical tests have proved that the new material: regolith + binding agent is a feasible construction material. . For practical application on the lunar surface however, extra MgO as well as the binding agent MgCl2, would need to be transported from Earth, making large-area stabilization difficult to sustain due to heavy reliance on feedstock materials from Earth.

Figure 13 - Lunar Habitation, Foster and Partners, ESA, 2012

Another trajectory, is laser sintering combined with 3D-printing to obtain fine structures. In 2012, V. K. Balla et al. were the first to sinter lunar regolith using a 0.5kW laser [4]. The spot size of the laser beam was 1.65mm, the thickness of the deposited layer was 254µm and the scan speed was 20mm/s for a powder feed rate of 12.36g/min. To ensure a good adhesion between individual layers, approximately 30 percent of the previous layer is re-melted. They were able to obtain dense solid cylindrical parts (Ø8-10mm, height 25-30mm) without any macroscopic defects at only a laser power of 50W. Later, M. Fateri et al. built a 10x10x3mm cube as well as a nut with a 100W laser. They noticed the transformation of the regolith into an amorphous structure [5]. The crystal structure present in the powder was eliminated during the melting and re-solidification. In addition, they created complex geometrical shapes such as µm-size gear to prove the total feasibility of a SLM process with regolith.

NASA has also funded a project that deals with 3D printing for lunar habitation. At the University of Southern California, a project team established a variety of scenarios with the printing method of contour crafting. Tests of printed elements were performed. A range of scenarios were developed such as a lunar landing pad and blast apron, a dust-free stabilized road, thermal shade walls and micro-meteorite protection shields, habitats and observation towers. Application for disaster areas and informal settlements were also proposed as well as combinations of single scenarios and 3D printed elements; all prototyping was done up to TRL 3 (laboratory tests).

On Earth, solar sintering has already been achieved by the artist Markus Kayser in the Moroccan desert [6]. He was able to create pieces of art with a rough but solid structure.

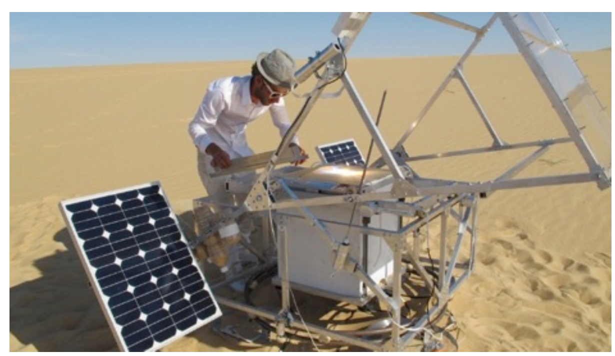

Figure 14 - Markus Kayser Solar Oven, 2011

6 Results and discussion

This section summarizes the results of project RegoLight at the time of publication. The findings of the material tests from two solar sintering campaigns (I: February 2017; II:

August 2017) are related in this section. An amended version of the interlocking building elements for the Mobile Printer August Campaign, and the implications for further developments are also described here.

6.1. Results from printing campaign I

The FPCU was successfully integrated with the FEMA, the NGCU, and local interfaces (solar simulator shutter) at DLR. The configuration and performance of the controller was as per requirements, where the FPCU was triggering the flow of regolith after the completion of a new layer, triggered by the closing of a cooled wall when sintering was not necessary. During the integration, the NCGU was used to convert a 3D model based on a CAD model into a file that is interpreted by the 3-axis table machine (Numerical Code). The NCGU generated a file that specifically targeted the solar sintering process, with its specific ad-hoc steps.

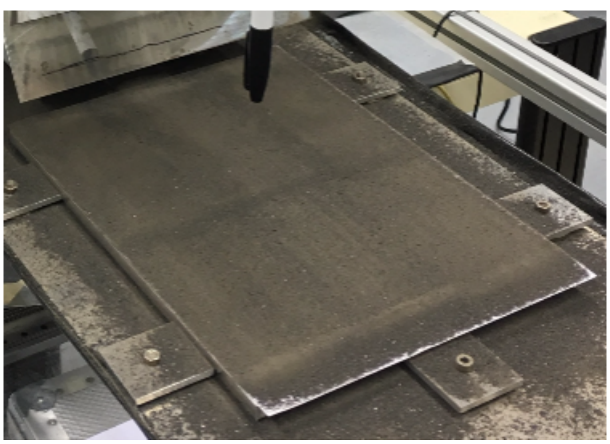

Figure 15 - Feeding process test results in the Ambient System, Credit: RegoLight consortium

The process was run under the solar simulator, consisting of an array of Xenon lamps, producing sets of solid parts after various optimizations of the system that included feeding rates and feeding strategies.

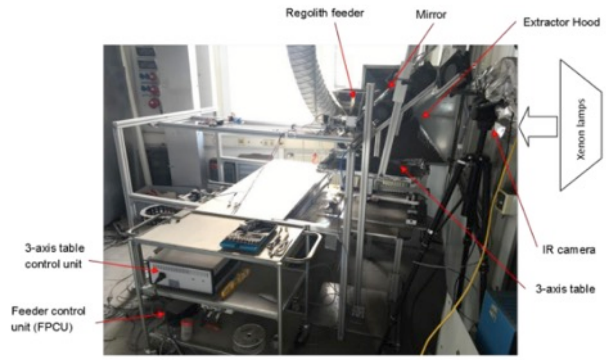

Figure 16 - Test setup for ambient printer, Credit: RegoLight consortium

Various test geometries were successfully sintered under ambient condition using the previously described setup. Test geometries, such as cuboid-shape, triangle-shape and S-shape samples were more successfully manufactured; while the sintering of spherical parts and interlocking elements found to be challenging due to the limited resolution of the printing head. Figure 18 shows an S-shaped, 3D printed piece, at the end of the printing process and after subsequent post-processing clean-up steps.

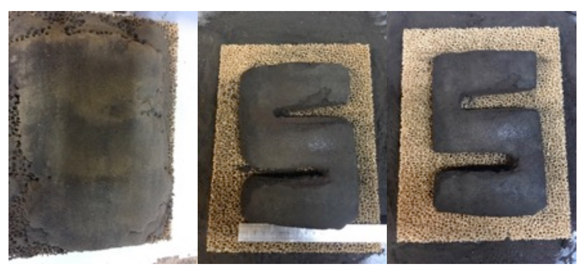

Figure 17 - Solar 3D printed S-shape piece at the end of sintering process (left), after removing the loose powder (middle) and after sand polishing (right). **Credit: RegoLight consortium**

6.2. Material test – structural analysis

Two solar sintered bricks were cut to obtain the samples used for compression and bending tests: one small 65 x 145 x 45 mm, and one large 120 x 200 x 20 mm. The small brick had better connections between the layers due to the shorter sintering time. For compression tests, the samples were covered with mortar to provide flat, even surfaces for contact with the testing machine. The samples from the small brick were 10 x 10 x 20 ± 5 mm and the ones from the large brick were 20 x 20 x 20 ± 2 mm. A picture of a typical sample is shown in Figure 19.

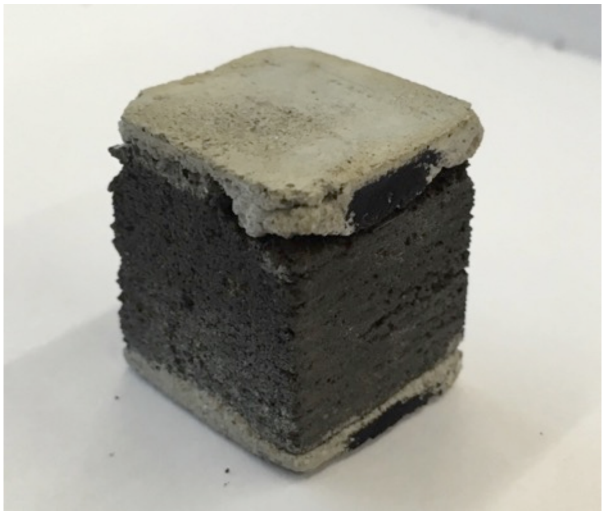

Figure 18 - Solar sintered sample, 20 x 20 x 20 mm³, used for compression tests, photo credit: DLR, 2017

Mechanical testing was performed perpendicularly to the layers. The stroke was 0.5mm/min. Although the results obtained with the samples from the small bricks were expected to be better, the small sample size, more sensitive to sintering defects, lowered down the mechanical properties. The compression strength for both kinds of samples was therefore similar. An average is given in the Table 2 below:

Table 2. Compression Strength (C.S.) and Young's Modulus (Y.M.) of solar sintered samples. Standard Deviation (S. D.) was also added. Average on 20 samples.

	C.S. (MPa)	S.D. (MPa)	Y.M. (GPa)	S.D. (GPa)
Solar Sintered lunar regolith	2.49	0.71	0.21	0.15

As for the bending tests, more samples cut from the small bricks were 10 x 10 x 40 ± 5 mm and tested parallel to the layer's plane. The large brick provided larger samples, 10 x 20 x 70 ± 5 mm that were tested perpendicularly to the layer plan. (Figure 20)

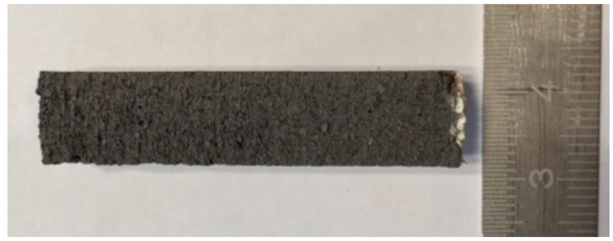

Figure 19 - Solar sintered sample used for bending test, photo credit: DLR, 2017

The testing of the samples was performed with 3-point bending equipment. The stroke was 0.5mm/min. Results of the tests are presented in Table 3.

Table 3. Flexural strength and Flexural Young's Modulus (Y.M.) of solar sintered samples. Standard Deviation (S. D.) was also added. Average of 30 samples.

	Flexural strength (MPa)	S.D. (MPa)	Flexural Young's Modulus (GPa)	S.D.(GPa)
Samples tested parallel to the layer's plane	0.55	0.33	0.11	0.08
Samples tested perpendicularly to the layer's plane	0.23	0.1	0.03	0.02

6.3. Results from printing campaign II

Campaign II was conducted in August 2017 for testing the Mobile printing head setup. Preliminary results include the production of numerous layers of sintered material with this novel system, and the improvement of the resolution of the sintered piece (1 cm instead of 2 cm) with respect to the printers running at the large solar simulator.

Figure 20 - Example of printed layer with enhanced resolution of mobile printing head, photo credit: Space Applications Services, 2017

6.4. Geometries of interlocking building elements

For the first campaign in February 2017, the tetrahedron element was chosen to be printed after the test geometries. The results showed that the light beam diameter of 20 mm was too big in respect to accuracy of the interlocking element and the building volume of 250x150x100 mm. It was decided to develop an amended geometry, avoiding sharp angles.

For the large solar sintering machine with the mobile printer head, LIQUIFER Systems Group developed a revised interlocking element with better interlocking capabilities and less sharp angles. This element is based on space fillers, which are defined as geometric bodies that can be clustered, filling up space entirely without leaving gaps. For RegoLight the rhombic dodecahedron was used as a geometric basis for interlocking blocks composed of clusters of basic elements, such as shown in Figure 23.

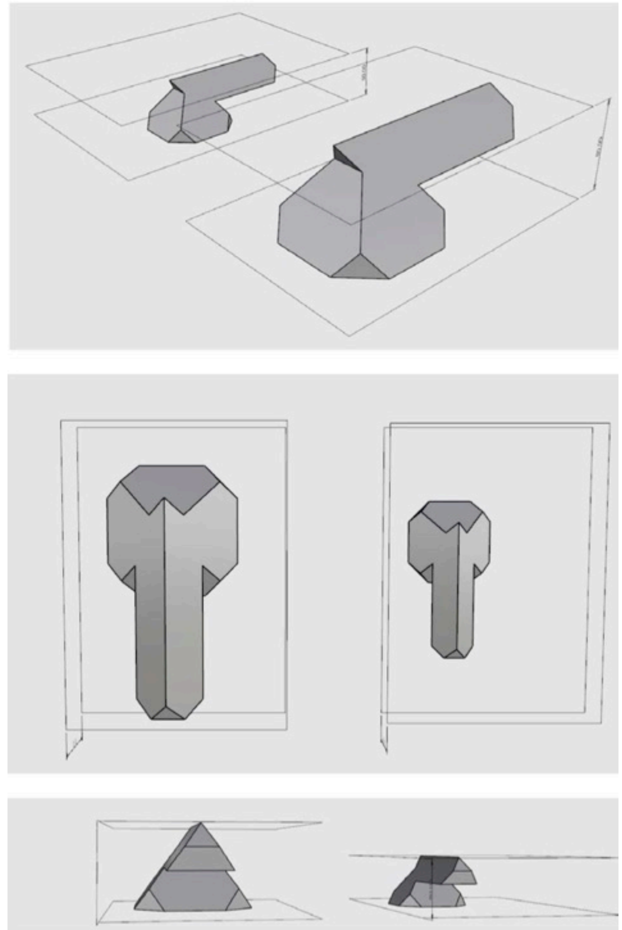

Figure 21 – Tetrahedron interlocking element used in the February 2017 campaign.

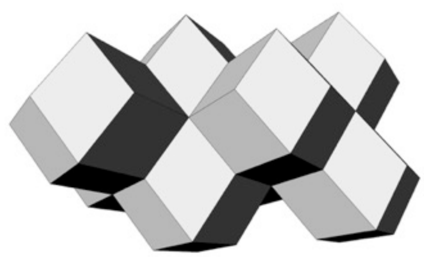

Figure 22 – Interlocking Element composed of rhombic dodecahedra developed for the August 2017 campaign.

The resulting rhombic dodecahedron based elements have equal interlocking capabilities in all 3 dimensions x,y,z. Each element can be turned in any axis in an orthogonal system keeping its interlocking compatibility. Thus, straight walls, corbel vaults and domes of accordingly modified elements can be erected.

The advantages of the shape, lie in its capacity to interlock in three dimensions, and its potential to fill space without leaving any gaps, relevant for radiation protection on the moon. The Rhombic dodecahedra permits agglomerations comprised of a variety of elements with interlocking properties.

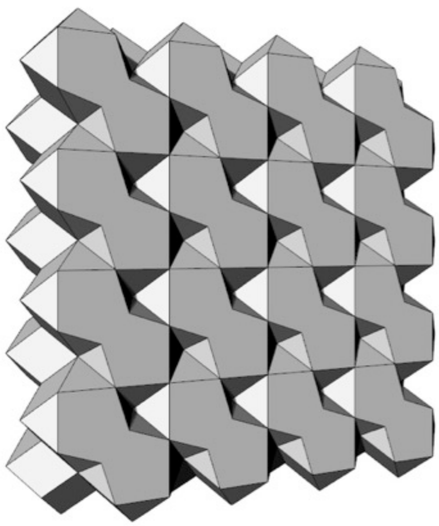

Figure 23 – Example wall of rhombic dodecahedron interlocking elements.

Since the upcoming campaign in the vacuum chamber has only very little volume for printing (120x170x15mm), a rather flat element for surface battlement was chosen from the initial collection of interlocking elements derived for different scenarios (see Figure 25).

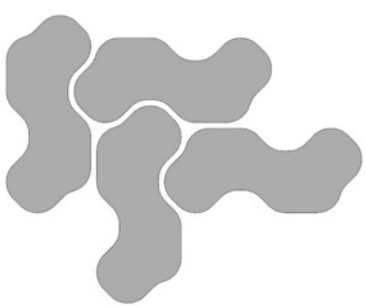

Figure 24 – Interlocking building element proposed for the vacuum printing campaign foreseen in September 2017.

7 Conclusions

During the project, several challenges have been identified regarding the materials science and materials physics of the sintered and un-sintered raw material. Wetting properties,, and material composition and transformation all require a more systematic understanding. Hence, future developments will likely involve greater input from the physics and engineering side to make sure more reliable results can be obtained.

In addition, sustaining a proper vacuum environment has been shown to be challenging for a ground-based facility; and will result in a suboptimal size..

Solar sintering is a unique AM technique which uses only the sun and sand as building material to produce building elements; making it an ideal way of constructing future habitats on the moon, where these materials are of great abundance. Up to date, no fully functioning solar oven has been developed which can work under vacuum capable of producing a strong and solidly integrated material made from loose soil simulant. Project RegoLight develops three test-beds, each with a different focus: testbed 1, a mobile printer head; testbed 2, automated x,y,z table; testbed 3, printer that can work under vacuum to advance the technology to a TRL 5. At the same time, sintered pieces are examined and improved in each successive print campaign. The three RegoLight printers contribute to the accumulating knowledge that will someday bring humankind to settle on the moon. RegoLight has also offered visualizations for such scenarios and a catalogue of interlocking elements that can be solar sintered. The RegoLight project also looks forward, with partner institutions already planning to take the next technology advancement steps, sintering stronger material, in a larger vacuum chamber, under realistic lunar light conditions.

8 Acknowledgements

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9 References

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