Robotic prototypes for the solar sintering of regolith on the lunar surface developed within the Regolight project

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Abstract

Future missions to the Moon will require the utilization of the local resources in order to make them affordable. The EU-funded RegoLight project advances existing 3D printing technologies and methodologies for the purpose of shaping lunar regolith, a readily available resource on the Moons surface, through the means of concentrated sunlight that sinters the material, making it solid. An electromechanical feeder system operating in ambient conditions inside a solar simulator has been developed in the context of the RegoLight project as well as the software chain enabling the conversion of building blocks in CAD format, into printing paths for the robotic elements. Two further systems are being developed, a TRL5 3D printer capable of operating in vacuum and dusty conditions, and a TRL4 mobile printing head capable of sintering regolith simulant, as a proof of concept of a system to be deployed on the Moon. Challenges include the correct transportation and deposition of the granular material, the dusty environment affecting mechanical and optical components, and systems exposed to high temperatures in vacuum conditions. Lessons learned from the engineering of these prototype robotic systems are shown.

1. Introduction

Missions to planetary surfaces and to space in general, are strongly limited the cost to deliver hardware to the target location. The gear ratio (mass needed in LEO/mass delivered to the Lunar surface) for Polar outposts is 4. This means that for every tonne delivered to the surface, 4 tonnes need to be sent to LEO [1]. High launch costs call for solutions to enable such missions.

In-Situ Resource Utilisation (ISRU) is an approach for transforming local resources into other products needed for the mission. This approach is believed to provide an affordable solution for sustainable manned presence in space [2] by enabling mass savings that allow having the same intended surface infrastructure, for a lower cost.

Additive layer manufacturing (ALM) methods adds material layer-by-layer to construct geometries. sintering is a method, compatible with ALM, of joining a powdered material by heating it to the melting point, and letting the grains fuse together to create rigid parts [3]. Sintering can be achieved in various ways that allow heating the material, most notably heating through an electrical resistor, through microwaves, and through solar concentration.

The advantage of solar concentration (the method used in the RegoLight project) over other methods is the direct use of solar energy, without the need for additional conversion and storage.

A number of possibilities can be considered for the energy delivery of solar light. The DLR solar oven routinely performs delivery of solar light through the use of a heliostat, a large concentrating mirror, and a final flat mirror that delivers the beam perpendicular to the horizontal plane.

Systems permitting additional mobility than that of large solar concentrators have been proposed: Nakamura and Smith [4] have demonstrated it is possible to collect solar radiation through an array of dedicated concentrators, delivering light into an optical waveguide composed by low loss optical fibers and quartz rods; Gonzales-Pardo and Denk [5] describe a solar concentrator capable of providing a vertical beam onto a surface with a single mirror; and finally, Hintze [6] used a Fresnel lens to melt the regolight, achieving sintering of a single layer at a depth of about 6 mm.

Sintered regolith is a promising candidate technique for the fabrication of planetary surface infrastructure, in particular of:

- Launch pads
- Launch site blast shielding berms
- Roads
- Radiation, thermal and micro meteorite shielding for habitats
- Foundations and leveling structures
- Equipment shelters
- Protection surrounding dust-free zones
- Blocks for the accumulation of heat

2. The RegoLight project

The RegoLight project is an undertaking aiming to increase the technology readiness level (TRL) for 3D printing utilising Solar energy to sinter lunar regolith. At the start of the project, the solar sintering of regolith is in TLR 3, where bricks have been successfully produced using a breadboard set-up in laboratory conditions using a solar simulator, and work is being done to advance to TLR 5 which necessitates functionality in the relevant environment.

In order to increase the technology readiness level of state-of-the art ALM techniques used in ISRU applications, a number of experimental setups have been designed and tested, namely; an Ambient System, a Vacuum System and a Mobile Printing Head, the characteristics of which, are compared in table 1.

All three systems are based on the same principle; using guides to translate either a beam or print-bed, using concentrated energy flux to sinter with an accuracy of displacement less than 1 mm and to use a feeder to deposit material with a layer thickness less than 0.1 mm. Further, the systems have to be operational in a dusty environment, and be sufficiently protected from heating.

The material used for the sintering is Lunar regolith simulant. The JSC-1 line of simulant, is derived from basalt with similar properties to that of lunar mare regolith, and excavated from volcanic ash deposits in Arizona, USA [7]. The simulant used in this experiment has the designation JSC-2A, and is considered to be a clone of JSC-1A [8]. As material properties for the JSC-2A is difficult to come by, where properties are lacking, the parameters of JSC-1 and samples brought back from the Apollo program are used, as it they have the same composition.

Colozza [9] studied the thermal properties of regolith samples brought back from the moon during the Apollo 14 mission. They determined that the phase change in the material occurred at around 1100°C, and they proposed a method of calculating the specific heat capacity as a function of temperature. Further, Gaier [10] determined that the JSC-1 has an abosrption index of 0.82.

3. Ambient system

The ambient printer system (Figure 2) has been designed to work at DLR's solar simulator facility in Cologne, which supplied a concentrated beam from a set of Xenon lamps, with a continuous energy flux of 1.1 MW/m^2. A 3-axis translation table and a regolith feeder was incorporated into the facility to allow for sintering of geometries in a layer-by-layer fashion. The 3-axis translation table had a requirement of a work envelope of $250 \times 150 \times 100$ mm^3. A margin was added to this requirement, resulting in a table capable of a work envelope of $280 \times 200 \times 110$ mm^3. Considering that the regolith simulant has a bulk density of 2000 kg/m^3, the system can produce a brick of regolith up to 12.3 kg.

3.1. Feeder unit

The regolith feeder unit has the task of depositing regolith powder between layers. To ensure that the required amount of regolith is delivered in a defined time window, three augers were coupled through a gearbox powered by a stepper motor. The *feeder control* consisted of a micro controller driving a stepper motor.

The regolith was stored in a hopper above the screws, to continuously supply materian when operated. The hopper was sized to prevent clogging of the material, and had a

Table 1: Comparison of the 3 systems

Version	Ambient	Vacuum	Mobile
Environment	Ambient, lab	Vacuum, lab	Ambient, outdoors
Movement	Moving tray	Moving tray	Moving printing head over fixed surface
Max envelope	.25m×.15m×.1m	.2m×.1m×.1m	.9m×.45m×.45m
Purpose	Solar sintering of samples with fine structure	Test without convection	Representative proof of concept of robotics

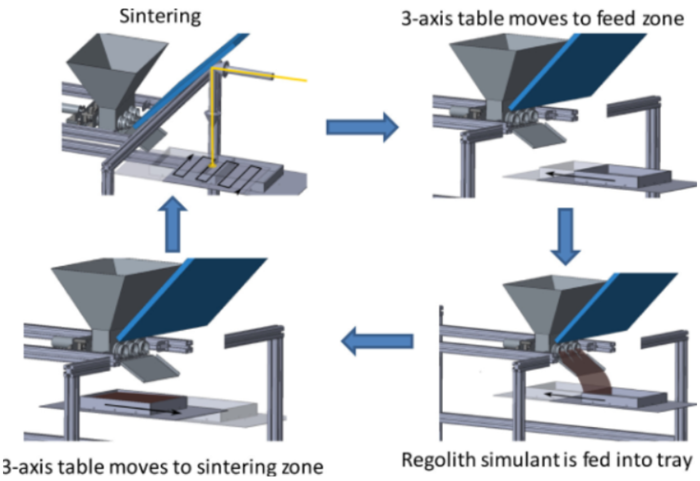

Figure 1: The Ambient System concept. Image: Space Applications Services/Regolight consortium.

capacity of ≈ 7 liters, which would intermittently be manually refilled during printing of larger components. Additionally, an experimental stamper was mounted on the underside of the feeder with the intent of packing the regolith after deposition to improve compactness.

A ramp mounted at a steep angle was used to transport the regolith to the print-bed. A vibrator was mounted on the ramp in order to improve the flow of regolith, as the powder has a tendency to "*stick*" to surfaces.

It was deemed necessary to implement a mechanism to spread the material in order to improve the homogeneity of the deposited layers. Various options were fabricated in rapid prototyping and tested, and the one that offered the best spread (the Pyramidal Wedges spreader) was selected (Figure 3).

Upon testing the functionality of the feeder, fitted with the spreaders, it was observed that only two passes did not provide a fully homogeneous distribution, but two passes and a randomization of the distances between passes resulted in adequate coverage. Additional passes beyond this added too much time between each layer to justify a small increase in layer coverage.

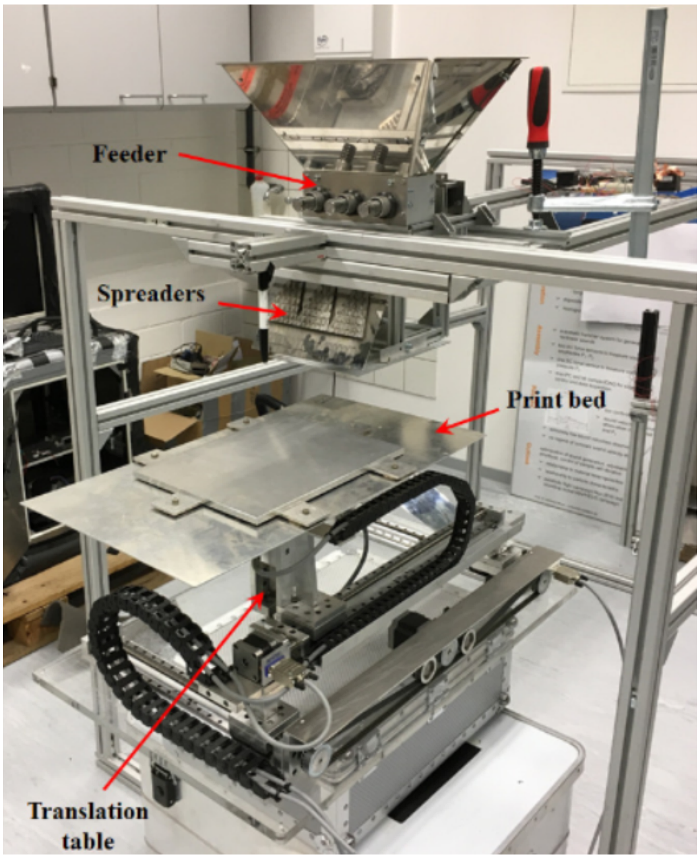

Figure 2: The Ambient System used during the test campaign. Image: Space Applications Services/Regolight consortium.

3.2. 3-axis translation table

A COTS 3-axis translation table moves the print-bed with the accumulating layers of regolith under the sintering light beam. The table moves during the feeding process, as the feeder unit and beam are stationary. The *table control* was done using a COTS XYZ controller.

3.3. System control

The electro-mechanical subsystems, namely the feeder unit and the 3-axis translation table, were individually controlled by a centralized system controller. Using a slicing software, STL files could be reduced to a numerical control code, commonly used for CNC and 3D-printing

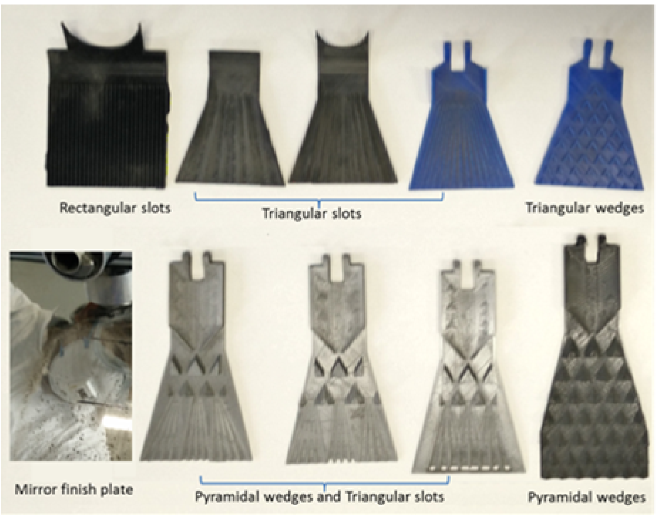

Figure 3: Spreaders, including the selected Pyramidal Wedges spreader. Image: Space Applications Services/Regolight consortium.

operations. A script for configuring the code was made which modifies the code to add feeding command.

3.4. Results

Once the regolith feeder and the 3-axis table synchronized, the solar sintering took place. Sintering about 100-micrometer thick layers, parts built up slowly. Due to the resolution of the solar beam, around 14 mm wide, and the limited printing area, it was not possible to sinter parts with too many details. A successful additive manufacturing of various shapes was however possible. For instance, Figure 4 shows a 3D printed S-shape part after removing the unsintered powder around it at the end of the process.

Figure 4: 3D-printed S-shape part with the Ambient system inside solar simulator. Image: DLR/Regolight consortium.

4. Vacuum system

To expand on the ambient demonstration performed at DLR's facility, an experiment using a vacuum chamber has been scheduled, and a vacuum rated setup capable of operating at 1×10^{-4} mbar is to be defined. This is done to simulate the moon environment, where convection is not present. Here, the ambient setup described above had to be scaled down to fit in the limited available volume in the vacuum chamber, with a diameter of 600 mm and height of 374 mm.

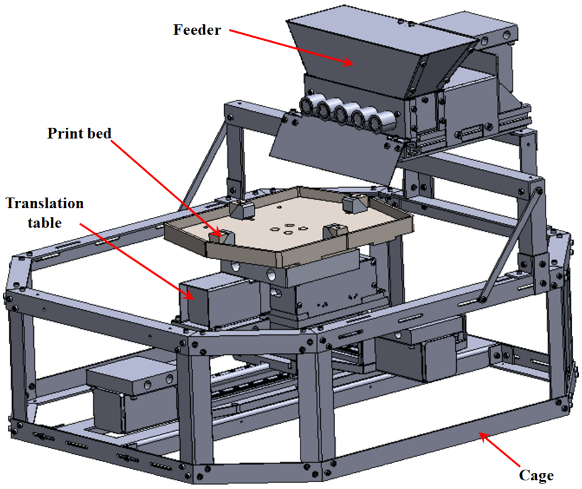

Figure 5: CAD rendering of the vacuum setup. Image: Space Applications Services/Regolight consortium.

4.1. System design

For this, the feeder was overhauled to a more compact model. The hopper size was reduced to have a capacity of ≈ 0.3 liters, the ramp was shortened as the print-bed will be closer and the stepper motor was replaced with one that is vacuum rated. Further, a structural frame around the setup was made to provide mounting points for equipment. Attention has to be paid to material selection, as the vacuum environment poses the problem of cold-welding. A vacuum-rated 3-axis table is to be used, being especially vulnerable to powder particles penetrating into the linear guides. To mitigate this, a multi-layer shroud is to be mounted below the print-bed and anchored on the surrounding support structure, providing a barrier for the stages. The setup had a required work envelope of $200 \times 100 \times 15$ mm^3. Simulations showed heat would be of greater concern with tespect to the ambient system due to the lack of natural convection to cool down sensitive equipment, and the compact nature of the setup. As the stepper motors are susceptible to over-heating, a heat-sink will be mounted on all four motors and connected to a liquid cooled loop which pumps water in and out of the chamber. Additionally, the shroud will also provide protection from radiative heat that would otherwise fall on the stepper motors. Temperature probes are implemented on the stepper motors, to allow for continuous monitoring.

4.2. Expected results

Solar sintering lunar regolith simulant under vacuum should lead to a very different end-product with different challenges than the ones faced while sintering in air. A positive impact will be the lack of convection, responsible for the non-homogenized cooling of the layers, sintering at 1 bar pressure. Sintered layers will also cool down slower thus increasing the interlayer bonding and the overall strength of the material. Some negative impacts should however take place. The regolith out-gases substantially during sintering. Additionaly, a problem may be present that was not a major concern in air: out-gassing under vacuum might lead to material projection on the hardware and could obstruct the window of the vacuum chamber. This outgassing will also increase the pressure inside the chamber, leading to the formation of new convection flux if the pump cannot reduce the pressure quickly enough. For this, gas jets for the cleaning of the window are foreseen. Regarding the end-product, some out-gas will likely be trapped inside the partially molten regolith, creating large close pores. The regolith sintered under vacuum is therefore expected to be more of a foamy structure.

5. Mobile Printing Head

The intention of the Mobile Printing Head is to demonstrate the feasibility of sintering of regolith simulant in a layer-by-layer fashion by using concentrated sun-light, as a proof of concept of a system to be deployed on the Moon.

From the proposed methods adequate for mobility, [4], [5], [6], the use of a Fresnel was chosen, given that it considerably simplified the implementation of the optics (while adding some acceptable complexity to the software). The Fresnel lens also provides a lightweight alternative, as a 2 kg lens can achieve the desired solar concentration.

[6], describe open issues with the method:

1. a solar concentrator consisting of a single lens must move to follow the sun while keeping the focal point at the desired area and
2. it is difficult to heat to great depths or wide areas.

In order to address (1), an automated system could scan the surface while tracking the sun, and in order to address (2) superficial sintering, using the RegoLight technique, could be done layer-wise instead of melting of the material, followed by deposition of material using the RegoLight feeder.

Robots such as NASA ATHLETE provide a gantry-like platform that can be used by a regolith sintering system, integrating a walking feature, which allows less massive wheels and provides additional functionality, and in combination with precise metrology and/or visual servoing [RD 8.], it can provide all the necessary capabilities to do additive manufacturing of large structures, for instance, with the RegoLight process.

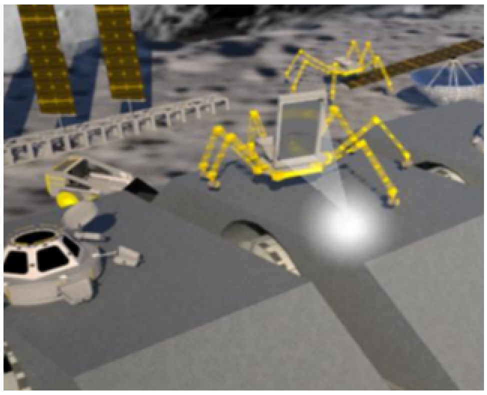

Figure 6: Concept of a mobile printing installed on an ATHLETE-like robot. Image: Space Applications Services/Regolight consortium.

In order to leverage the developments made by JPL in ATHLETE, the team uses ATHLETE as a reference for a future baseline means of displacement for a potential mobile printing head on the Moon (Figure 6).

In order to implement the RegoLight prototype, and in the absence of an ATHLETE-like robot, the team has implemented a Fresnel lens mounted on a gantry designed to translate in the XYZ space, allowing for sintering on a stationary print-bed as opposed to the ambient setup described in Section 3. For this, accurate sun tracking and translation guides are required. Using off-the-shelf components combined with the feeder unit described above, an experimental setup was designed, built and operated. The guides are capable of providing a work envelope of $900\times450\times450$ mm^3 and a maximum translation speed of 100 mm/s.

Due to natural convection, the temperature of the test specimen might drop below the target 650°C required for appropriate layer adhesion. Therefore, a requirement is to provide means to avoid this.

5.1. Sun position

The position of the Sun is defined by the elevation and azimuth angle relative to a fixed local point on earth. Using the method proposed by Michalsky 1988 [11], the Sun's ephemeris could be calculated for a given date and time. Figure 7 shows the path of the Sun on the 21st of every month in the year, at the GPS location of Zaventem, Belgium. Based on geometrical calculations, as well as experimental testing, it became clear that the lens used could not provide adequate solar concentration at angles lower than 35°. Using this information with the fact that the azimuth angle can be divided by 15° to convert from angles to hours, it was determined that during the summer solstice of the year, the total print time could be as long as 11 hours, while during the autumn equinox there is up to 4.5 hours of available time.

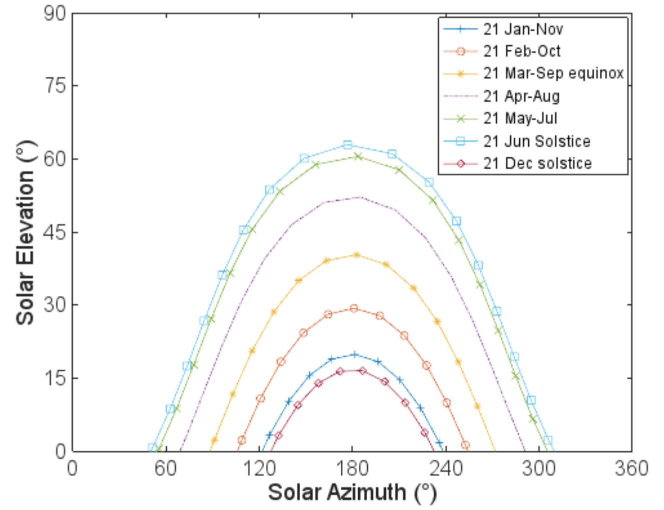

Figure 7: Variation of sun elevation angle. Computed using the method proposed by Michalsky 1988. Image: Space Applications Services/Regolight consortium.

Figure 8: Sintered lines made on the JSC-2A lunar regolith simulant during preliminary testing. Image: Space Applications Services/Regolight consortium.

5.2. Heating

Considering a lens with a height of 950 mm, width of 690 mm, a beam spot diameter of 10 mm and an assumed transmission index of 0.75, results in a magnification of 6300. From this one can estimate that the concentrated solar flux, based on the reported 1000 W/m^2 at sea level [12], on the order of 6.3 MW/m^2. In order to estimate the required scan-speed of the lens during operation, the internal energy equation was used. Since the energy input is assumed to be much larger than the losses, they were excluded in the calculations.

$$Q_{sinter} = c\rho Ah(T_{final} - T_{ambient}) \tag{1}$$

Where Q_{sinter}, c, ρ, A, l, T_{final} and $T_{ambient}$ are the energy required to sinter, specific heat capacity as reported in [9], bulk density, beam point area, layer thickness, sintering temperature and ambient temperature, respectively. Incorporating the definition of heat flux (q_{sun}) and velocity, the variation of the scan speed as a function of supplied heat flux can be determined. Calculations were used to design and size the system (speed, power required to move the printing head).

$$v_{sinter} = \frac{q_{sun} d_{beam}}{c\rho l\,(T_{sinter} - T_{ambient})} \tag{2}$$

For the testing and operation, and due to the intrinsic limitations in the calculations, the precise speed for sintering was determined empirically.

5.3. The Fresnel lens

A Fresnel lens is a sheet of transparent material which consists of concentric prisms which refracts incident light similarly to a conventional lens [13]. The Fresnel lens has the advantage that is much more lightweight than a spherical lens of the same magnification capabilities. The magnification of the lens can be determined by dividing the area of the lens by the beam spot that it produces.

5.4. Print area

The print area is defined by the stroke length of the guides in the gantry. However, since the incident sunlight falls on the print area at an angle, the area itself changes during the day. See Figure 9 for an illustration of the effect. This elevation-azimuthal dependency of the print area can easily be determined by using simple trigonometry, with the focal length of the lens and the guide stroke as constants, and the angles as variables. By inserting the parameters defining the minimum and maximum angles for the Sun elevation and azimuth, i.e., morning, noon and evening, one can find the area that overlaps the three conditions where sintering could be performed continuously during the day.

5.5. Sub-systems

The assembled gantry consists of the subsystems: base, trolley, fork and lens and feeder. Figure 10 shows the a CAD drawing of the design.

5.5.1. Base

The base consists in a square frame onto which 2 linear guides are installed, each one with two carts being driven by a lead screw. In order to avoid de-synchronizations due to delays over the control network, a single motor is used, and a coupling is connected between the two guides. The means are provided to adjust the leveling of the entire structure.

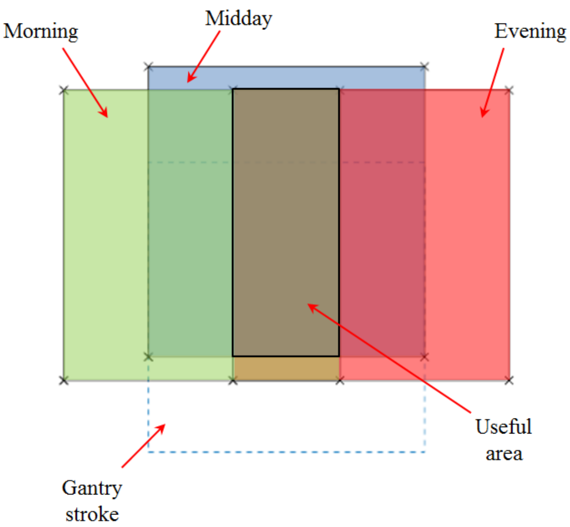

Figure 9: Elevation-azimuthal dependency on print area. Image: Space Applications Services/Regolight consortium.

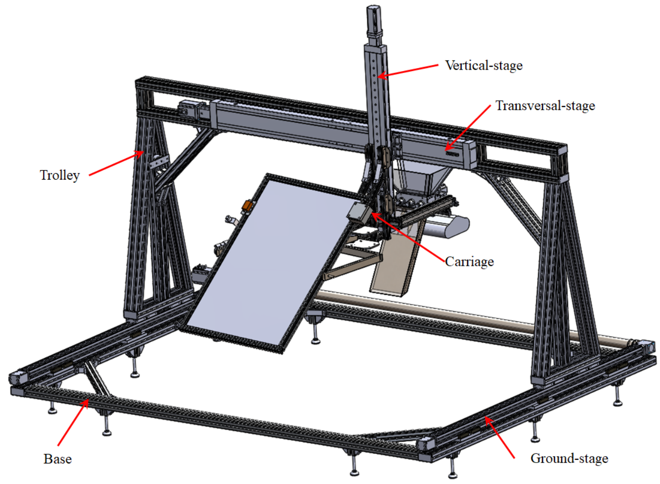

Figure 10: Illustration of the gantry-based Mobile Printing Head with all its subsystems. Image: Space Applications Services/Regolight consortium.

5.5.2. *Trolley*

A trolley assembly has been implemented, which operates on a set of linear guides located at the base. A set of two bifurcated vertical assemblies run on these tracks/linear guides at the base (each one on a set of 2 carts), and are rigidly connected by a transversal beam on top.

The trolley moves linearly along the guides located at the Base of the gantry. A linear guide installed on top of the transversal beam (Y axis) is driven through a belt system by a motor, and features a cart which moves accordingly, and onto which the Z stage is installed.

The Z stage has another motor that drives a cart up and down through a lead screw system. On this vertical cart, the Fork and Lens assembly is installed.

Two cross beams are used to hold the Y-stage in place, which in addition to support, provides a stiffening component to the gantry. As the carriage has a mass up to 50 kg and further components will increase this mass, some deflection would be expected to occur. However, due to the high area moment of inertia of the aluminium profiles, the maximum deflection should be less than 0.1 mm. To reduce the moment acting on the Y-stage, the centre of gravity of the carriage has to be as close to the stage as possible.

An A-frame configuration was chosen so as to increase the stiffness and stability during acceleration and deceleration. The lens on the carriage will stay clear of the posts at azimuth angles up to 75°, relative to the gantrys southward direction.

5.5.3. *Fork and lens*

The Fork and Lens assembly consists of a system able to rotate the lens in Azimuth and Elevation. Azimuth rotation is obtained by rotating the fork in yaw around an vertical axis close to the Z stage. Elevation is obtained by rotating the lens around an axis defined by the 2 extremities of the fork prongs.

For stability purposes, it is necessary to have a centre of mass for the Fork and lens Assembly and the Hopper (and associated material) as close as possible to the vertical axis defined by the Z stage. Since the material in the hopper is depleted during the course of the operation, it has been deemed convenient to have a CoM as close as possible to the vertical axis defined by the Z stage, when the material is depleted to 50-60%.

The Fork and Lens Assembly includes also an IR heater that is used experimentally in order to keep the sintered regolith as warm as possible when the system is idle, or when necessary.

5.5.4. *Modified feeder*

The feeder unit from the ambient system was reused and modified to allow integration into the Mobile Printing Head. As the feeder would be suspended much higher above the print-bed here than in the ambient experiment, a long stainless steel ramp had to be mounted. Additionally, the stamper would not be incorporated for the same reason.

5.6. *Control*

A set of software components control the Gantry, i.e. to move the different axes simultaneously to perform the trajectories and make the sintering on the regolith surface (see image 11). The azimuth and elevation of the lens is controlled independently with an analog electronics sun tracker.

5.6.1. *Low Level Controller*

The Low-Level Controller (LLC) consists of a set of software methods that enable a CNC code sender to access

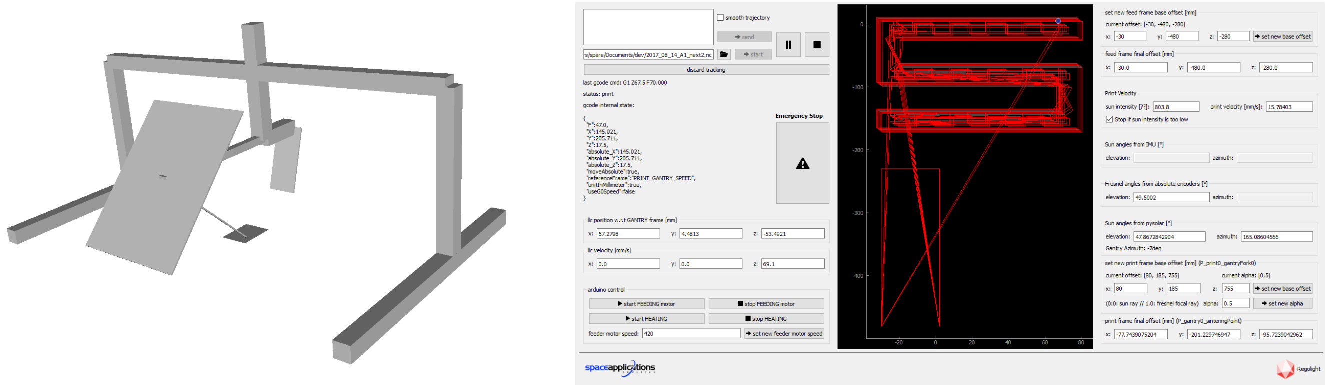

Figure 11: (Left) Real time 3D display of the Mobile Printing Head and Gantry during operations, (right) graphical user interface of the software developed for gantry operation. Image: Space Applications Services/Regolight consortium.

the services provided the servo motor driver. The choice for the servo motor driver provides high positioning accuracy and fine control over the velocity and acceleration profiles during motion. The LLC is developed in Python and wraps the Automation Libraries of the 3-axis drives with interfaces that are required for operation using the CNC code sender.

5.6.2. Numerical control code parser and CNC code sender

This part of the software converts a G-Code commands into trajectories that will be performed by the gantry axes. The orientation of the Fresnel lens is set by the position of the sun (its elevation and azimuth angles). The trajectory to sinter regolith is defined by the G-code command. Based on the kinematics of the system (the actual orientation of the Fresnel lens) and the sun intensity, the goal of the parser is to compute the trajectory of the center position of the lens based on the trajectory to sinter.

The CNC code sender script was developed to, on-the-fly, modify the CNC code during operation. It sends instruction to the LLC defining paths, and appropriate velocity.

5.6.3. Path planner

The numerical control code file provides the key points and the linear segments to create the shape of the CAD model. To sinter the regolith simulant properly, the focal point of the Fresnel lens should move at a specific velocity, without full stops in the trajectory, first to avoid any vibrations in the structure, and second to avoid oversintering or melting the regolith (due to a too long exposure of the focal point). To do so, the trajectories should be interpolated by taking into account the possible acceleration/deceleration of the system.

This removes the sharp changes in the trajectory, meaning that trajectory will go near the key points (depending on acceleration), but it wont go exactly through the key points, due to the fact that full stops are to be avoided. The objective is to get as close as possible, without compromising the process nor produce excessive vibrations.

5.6.4. Results

The demonstration of the proof of concept of a machine that can perform the sintering of Lunar regolith was performed (figure 13). The delivery of energy to the surface was successful, achieving sintering of the individual layers. A resolution of less than 1 cm (beam size) was achieved and a solid buildup of parts was attained. The movement of the large system was smooth and permitted the correct deposition and accurate displacement of the gantry, also thanks to dampeners that were installed to improve the stability of the printing head.

The outdoors elements influenced the printing, such as the presence of wind, clouds and the need to pause the process overnight. The presence of clouds was mitigated by implementing the pausing of the process when the sunlight was below a threshold, and the presence of wind by trying to surround the gantry with wind blocking surfaces, although this measures were only partially successful.

A part was obtained, albeit with the presence of intense delamination (figure 12). This is atributed to high thermal stress on the part caused by inter-layer cooling. Although the cooling between layers could not be fully avoided, none of the elements that are believed to play a major role in this excessive cooling are present on the Moon.

Figure 12: S-shaped part printed with the Mobile Printing Head. Image: Space Applications Services/Regolight consortium.

6. Conclusion and Future Work

An Ambient System and Mobile Printing Head System have been developed and building elements were fabricated. The former system was focused on the laboratory process leading to the printing of sintered specimens and building blocks inside the solar simulator at DLR; while the latter focussed on creating a proof of concept of a mobile printing system comparable to one to be deployed on the Lunar surface, and led to the printing of sintered specimens in an outdoors environment. Both tests were successful in their own objectives.

Regarding the sintered specimens, differences were found in the part printed by the mobile printing system, namely delamination due to thermal stresses caused by interlayer cooling, a consequence of the outdoors uncontrolled environment and the need to pause the process overnight.

A test is scheduled of a third element, a Vacuum System that will test sintering in an environment closer to the Moon, with the particular constraint/benefit of lack of convection.

Acknowledgement

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Figure 13: Gantry-based Mobile Printing Head assembled and in operation. Image: Space Applications Services/Regolight consortium.