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The MOONRISE-Payload as proof of principle for Mobile Selective Laser Melting of Lunar Regolith

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ABSTRACT

When setting up a lunar station, technologies for the use of locally available materials are crucial. Such technologies drastically reduce the need for transportation from Earth. We aim to provide proof of a key technology, namely Mobile Selective Laser Melting (M-SLM) for terrain modelling i.e. for building large structures such as launch/landing pads, but also building infrastructures like shelters protecting astronauts or equipment against radiation and micrometeorites on the Moon. The M-SLM technology has the advantage that only electrical energy and a moving system are required.

For M-SLM, a mobile high power laser beam is directed on lunar regolith leading to its melting. Subsequently, the melt cools down and solid structures are generated. The MOONRISE instrument should serve in a short-term mission as a proof-of-principle experiment for the M-SLM technology on the lunar surface. In a first step, an Engineering Model (EM) of our MOONRISE instrument with a volume of 10 cm x 10 cm x 15 cm and a mass of about 2.7 kg has been built and thoroughly tested on ground. It could be accommodated on a rover or a robotic arm to move the laser spot in order to create 1D, 2D and even 3D regolith structures on the Moon.

Recently, three new projects have been initiated in order to (1) develop the MOONRISE payload towards a Flight Model (FM) with accommodation on a commercial lunar lander, in order to (2) apply 2D laser beam deflection techniques for process scaling on a potential follow-on payload and in order to (3) investigate the detailed process of regolith laser melting under lunar gravity conditions in the Einstein-Elevator.

Keywords: ISRU, laser melting, additive manufacturing, sintering, lunar exploration, construction

1. INTRODUCTION

In-Situ Resource Utilization (ISRU) technologies pave the way for a sustainable colony on the Moon. Above all, the construction of structures using only the available resources is an important factor in reducing costs and logistical effort. The MOONRISE project aims to melt lunar regolith using lasers on mobile platforms for the additive manufacturing of structures. This process is called Mobile Selective Laser Melting (M-SLM) and has the advantage that only electrical energy and a moving system are required, e.g. for building large structures such as launch/landing pads and streets, but also building infrastructures such as shelters protecting astronauts or equipment against radiation and micrometeorites on the Moon. For a proof-of-principle experiment of M-SLM, which aims for creating 0D, 1D and 2D, and even 3D fused regolith structures on the lunar surface, we designed the MOONRISE payload. The MOONRISE payload can be accommodated on a rover or a robotic arm to ensure mobility for the melting experiments.

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Based on an internal trade-off between various methods for additive manufacturing of regolith we think that using a laser is the best option, since it is independent from the sun and enables good precision as well as the potential for building large structures. M-SLM can be fully automated. For M-SLM, a mobile high power laser beam is directed on lunar regolith leading to its melting and after cooling to the generation of a solid structure.

Laser-based processing tests of regolith and simulants have been performed so far solely in laboratories on Earth [1]. The underlying system technology for processes such as SLM® is complex. Structures are created layer by layer, which requires advanced powder processing and distribution system technology, which would in turn require large investments when being realized for application on the lunar surface. This can only be considered as a long-term goal as shown in the roadmap of Fig. 1. Within any type of laboratory experiments on Earth, it is not possible to fully simulate the lunar environment, resulting in potentially unrealistic processes. In addition, unknown effects can emerge on-site, which are completely unpredictable and which may have a big impact on processing results. With that lack of knowledge, it is not possible to plan realistic missions for the construction of infrastructures.

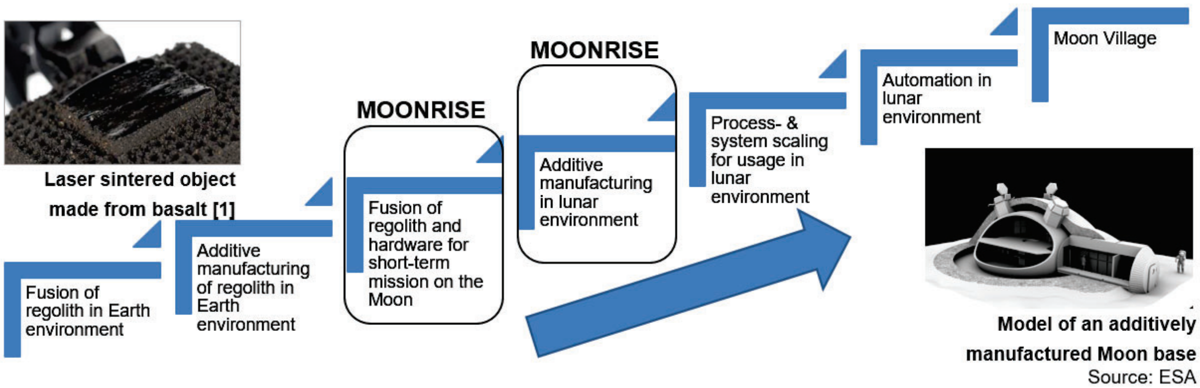

Figure 1. Roadmap for additive ISRU construction on the Moon.

Therefore, the two partners, Technische Universität Berlin (TUB) and Laser Zentrum Hannover e.V. (LZH), teamed up for the development of the MOONRISE payload. The MOONRISE payload is currently at post-PDR-status with a tested Engineering Model (EM) available. It consists of a high power laser capable of melting regolith at a fixed spot, i.e. creating 0D objects from fused regolith. However, by accommodating the payload on a rover or a robotic arm 1D and 2D objects could be created by the added mobility. The MOONRISE payload could enable a timely and inexpensive test of laser melting of regolith on the lunar surface. This direct proof of feasibility would significantly increase the technological readiness level of the M-SLM technology. It is expected that the additive processing of regolith will then be increasingly considered in concepts for exploring the Moon.

2. ENGINEERING MODEL DEVELOPMENT AND TESTING

Synthetic lunar soils, so-called regolith simulants, are typically used for experiments on Earth due to a lack of original material from the Moon. This enables realistic results, even if it is not possible to completely reproduce all the properties of the lunar soil and the prevailing environmental conditions. For the initial laboratory experiments, we used different variants of regolith, which were produced with the help of a modular regolith simulant system developed at TUB [2]. We placed the regolith simulants in a vacuum chamber at around 10^{-2} mbar. The regolith simulant was irradiated for the melting experiments by an external diode laser at a wavelength of 976 nm and a power of up to 140 W for several seconds. Melting was observed in the distinct optimized optical setup to start at approximately 35 W of optical power for less than 10 s. Spherical beads from melted regolith with a diameter of a few millimeters were produced (Fig. 2).

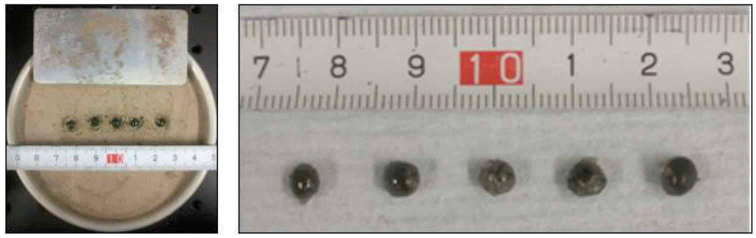

Figure 2. Laser melted regolith simulant spheres.

Moreover, it could be observed that a working distance of approximately 230 mm from the window is safe to protect the optics from contamination induced by the laser regolith interaction. With this laboratory setup, major design parameters for the payload such as beam guiding, working distance, spot size and optical power range could be deduced. The MOONRISE payload mainly consists of a printed circuit board (PCB) for system communication, a fiber coupled diode laser, an electrical diode driver, a beam focusing optics, and an LED illumination as depicted in the block diagram (Fig. 3). The visualization of the molten regolith structures will be obtained by external cameras of the rover or the lander.

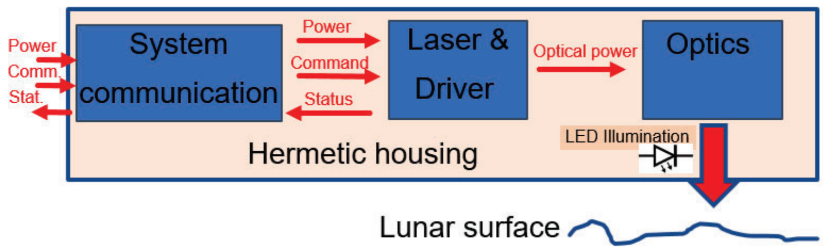

Figure 3. Block diagram of the MOONRISE payload.

For reasons of cost-efficiency, the EM of the MOONRISE payload was developed based on a high-risk approach by means of mainly using commercial off-the-shelf (CotS) components. These CotS parts were partly based on space heritage and have been screened in environmental tests and selected before. Also for the EM, a diode laser system with an output power of up to 140 W at a wavelength of 976 nm was chosen. Nevertheless, the package, beam shaping, and main communication and control electronic on a PCB are fully custom-made for this payload to meet the mission requirements. Custom PCB components meet the Automotive Electronics Council (AEC) qualification requirements [3]. Within this qualification, they passed load tests for high temperature operating life (HTOL) grade 1 which means they are proven to work within the temperature range from -40 °C to 125 °C. The laser system is designed for a working distance of 230 mm between the laser output and the regolith surface but is capable to conduct the melting process efficiently with a deviation of ± 30 mm. Even if the payload mission requires only operation times of a few seconds, the system is capable to operate up to several minutes at once and stays within its thermal boundaries without any active thermal control. To reduce the risk of failure of the used CotS components, the package is hermetically sealed and filled with dry air with low dew point to prevent condensation during cruise and surface mission. A lightweight version of this package is currently under development to reduce the mass of the payload. For baseline operation, a laser power of typically 70 W will be applied for 6 s to the lunar surface at a distance of about 230 mm. The LED illumination supports visualization of the molten regolith by external cameras. The MOONRISE payload can be accommodated on a rover or a robotic arm to ensure some mobility for the melting experiments. The EM, which is shown with its major specifications in Fig. 4, has been assembled and tested.

Parameter	MOONRISE
Optical output power capabilities	6 – 140 W **typ. 70 W**
Power consumption (laser on)	25 W – 340 W **typ. 175 W** for **6 s**
Mass	~2.7 kg
Dimensions	1.5 U (10 x 10 x 15 cm³)
Distance to ground	230 ± 30 mm
Operating temperature (tested)	-35 °C to +70 °C
Storage temperature (tested)	-50 °C to +95 °C
Vibration (tested)	16.3 g_{rms} (20 Hz – 2 kHz)

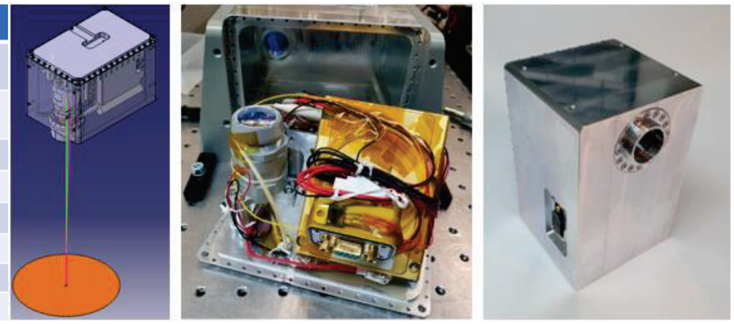

Figure 4. MOONRISE EM (from left to right): Major specification table, CAD model with laser beam, open EM, hermetically sealed EM package.

At first, functional tests with the MOONRISE EM attached to a vacuum chamber have been carried out. The melting and solidification of regolith were comparable to the initial laboratory experiments and are depicted in Fig. 5.

Figure 5. Regolith melting process with the MOONRISE EM: 1. Sample container with regolith simulant, 2. Start of the melting process: some simulant particles are ejected, 3. Melting phase: a sphere of molten simulants forms, 4. Cooling phase: the molten regolith solidifies amorphously, 5. Cooled and solidified sample.

The performance, i.e. optical output power of the MOONRISE EM at different temperatures was evaluated in a thermal vacuum test campaign (Fig. 6 left). The non-operating temperatures ranging from -50 °C to 95 °C did not lead to any damage or degradation of the payload. At low temperatures, the laser was able to produce more output power than expected in forehand. At the minimum operating temperature of -35 °C, for example, the output power was 15 % higher than at room temperature. Between 30 °C and 50 °C, the performance was good enough to fulfill all mission requirements. Up to 70 °C, the performance was sufficient for the minimum mission goal, which is the production of one spherical sample. The thermal-vacuum qualification campaign did not lead to any permanent degradation of the MOONRISE EM.

Sine and random vibration tests were performed for full qualification level (Fig. 6 right). This includes sine vibration up to 10 g with a frequency up to 100 Hz and random vibration with 16.31 g_{rms} in the range between 20 Hz and 2 kHz. These tests revealed a minor issue within the diode driver and thus showed the need to customize it further, which led to an improved design. The diode laser, the in-house-developed PCB, mechanics and all other optical elements passed all tests without any degradation or failure.

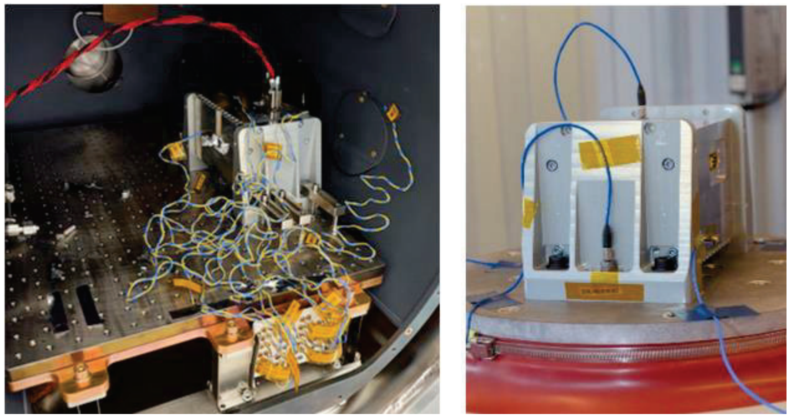

Figure 6. Environmental testing: MOONRISE EM in thermal vacuum chamber (left) and on vibration table (right).

3. FURTHER PAYLOAD VERIFICATION

3.1 Lunar gravity condition

For further verification, we obtained the unique opportunity to use the novel Einstein-Elevator at the Hannover Institute of Technology (HITec), University of Hannover [4]. The Einstein-Elevator is an active drop tower, which enables experiments to be performed under different gravity conditions. We integrated the MOONRISE EM setup (Fig. 7 right) into the Einstein-Elevator experiment carrier (Fig. 7 left).

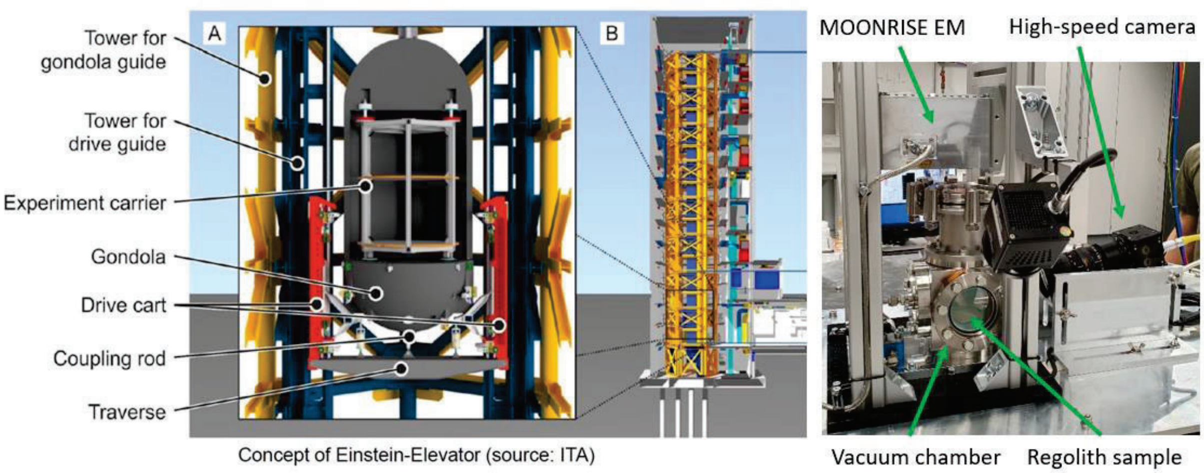

Figure 7. Schematic drawing of the Einstein-Elevator (left) and laser melting experiment prepared for the experiment carrier (right).

Several laser melting experiments of regolith simulants could be executed in two measurement campaigns not only under micro-gravity (≈0 *g*), but also under lunar gravity conditions (0.16 *g*) and compared to the experiments under Earth gravity. The tests were carried out under all three gravity conditions with an identical setup and laser parameters. The irradiation time was 3 s followed by 1 s cooling down for the distinct gravity condition. Due to the limited drop tower height and thus a maximum experimental time of 4 s at the different gravity conditions, the applied optical power was increased to 105 W. All generated samples have a spherical shape and a diameter of approximately 3 mm. The surface is glass-like and regolith particles are fused to the bottom side of the regolith spheres. Minor differences were found between the experiments under different gravity conditions and are described elsewhere in detail [5]. However, the process of melting regolith beads could be proven.

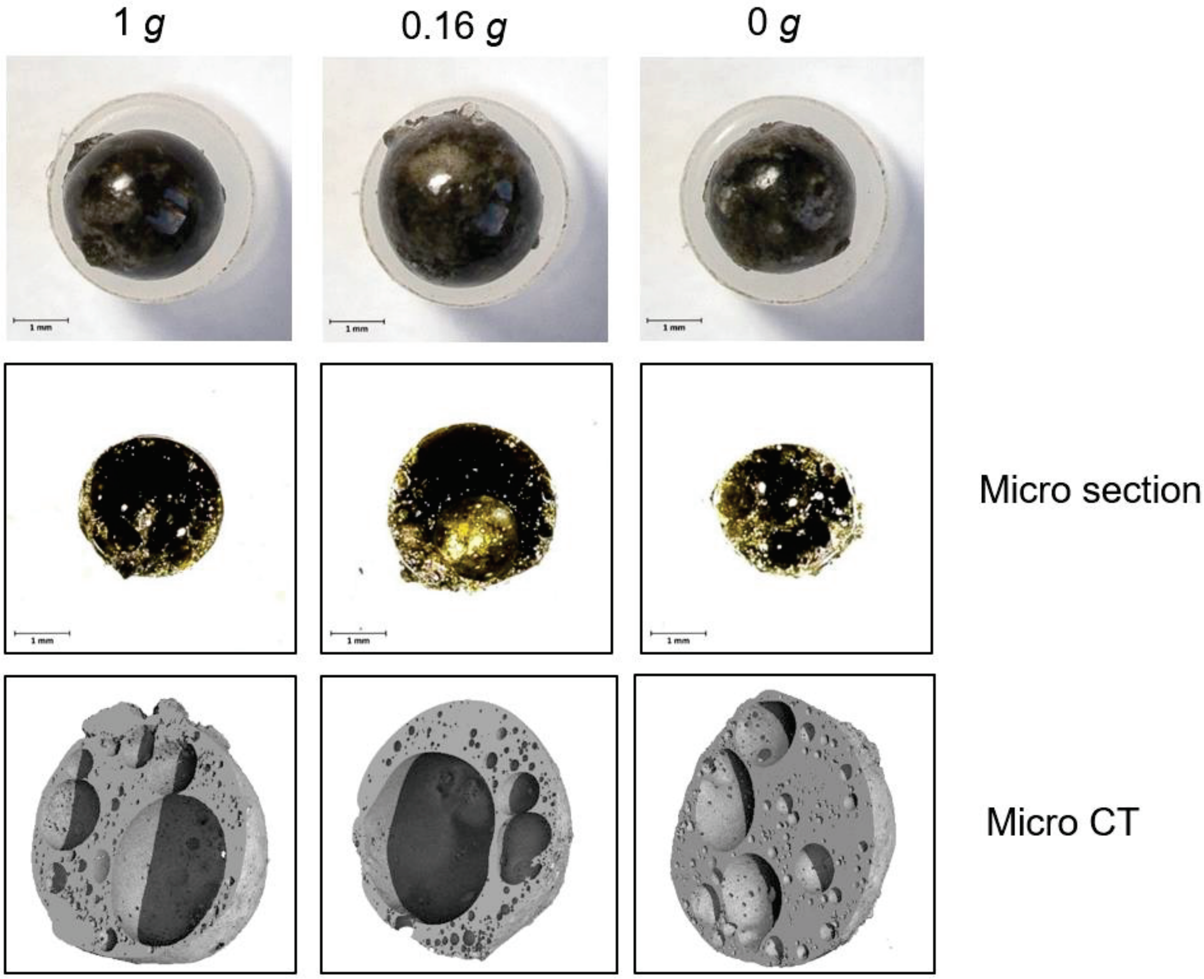

Figure 8. Typical samples of molten regolith, produced at 1 *g* (left column), at 0.16 *g* (middle) and at 0 *g* (right) gravity condition. The second row shows micro sections and the third row micro CT data of the processed regolith samples.

Follow-on measurement campaigns in the Einstein-Elevator are planned to be conducted in a recently approved novel activity fully focusing on the experiments under various gravity conditions. Here, also larger laser power levels up to 500 W will be applied. Moreover, larger structures shall be obtained by using the print-pause-technique during subsequent runs of the Einstein-Elevator. In addition, the process shall be modelled to forecast the material properties of the generated structures and the influence of different gravity conditions on the process.

3.2 Accommodation on a robotic arm

In addition, we attached the MOONRISE EM to a robotic arm ([6], Fig. 9 left). The goal of the experiment was to test the M-SLM process for the MOONRISE payload on a robotic arm for identification of parameters to produce flat rectangular specimens. This lays the knowledge foundation for the production of flat infrastructure on the lunar surface such as streets or landing pads. On the other hand, it is an important step for the production of three-dimensional objects using the M-SLM process. The experiment was carried out under Earth conditions, such as Earth gravity, Earth atmosphere and room temperature. The laser was positioned by the robotic arm so that its distance to the regolith simulant surface was constantly 23 cm. The laser power was set to 120 W and the moving speed of the laser to 1 mm/s by moving the robotic arm. With these parameters several lines were fused together and a solid 2D structure of 20 mm x 20 mm x 4 mm in size was generated (Fig. 9 right). The produced specimens had a mass of a few grams and varied in their mass by only a few percent. The method is reproducible despite the grain-to-grain variation within the simulant material that was processed. The samples had an amorphous composition with some embedded crystalline particles on the contact side with the simulant bed. The contact points of the individual lines molten by the laser are stable, which was tested by applying some load manually. Thus, it can be assumed that larger components can be manufactured with the process.

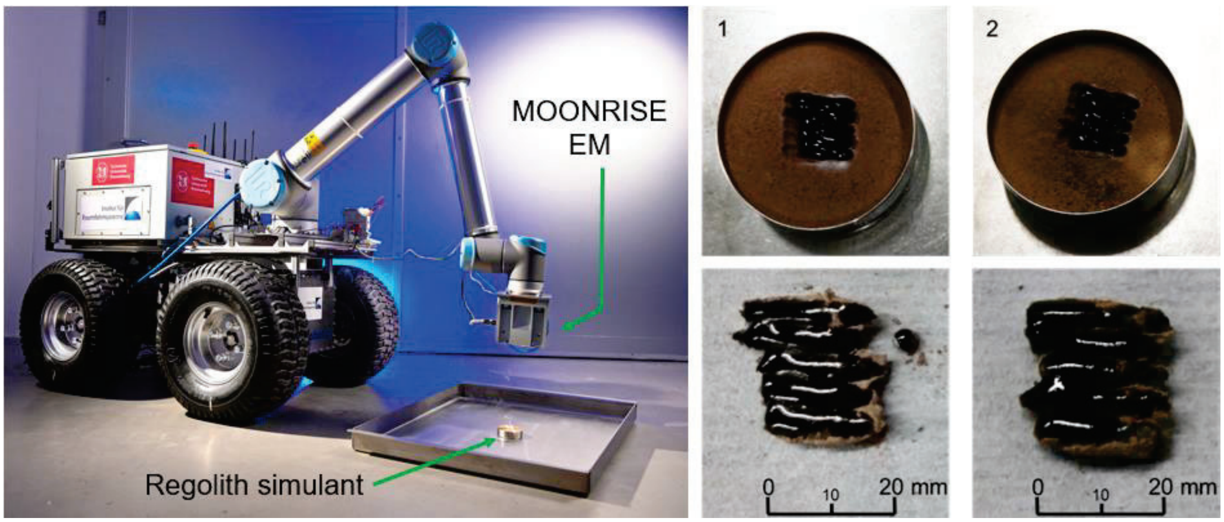

Figure 9. Typical samples of molten 2D-regolith structures (right) generated by attaching the MOONRISE EM to a robotic arm (left).

In order to generate larger structures without moving the rover or robotic arm each time, we will investigate in another recently acquired project the technology of fast automated 2D-beam deflection. In this project, we carried out a trade-off between different laser beam deflection technologies. It turned out that galvo-scanners are the most mature technology fulfilling all necessary requirements. However, MOEMS, which currently suffer from insufficient laser power handling capabilities have great potential, because they are extremely compact. Currently a setup is built to evaluate different scanning strategies in order to generate 1D and 2D structures and further optimize this process.

4. DEVELOPMENT TOWARDS THE FLIGHT MODEL

In a further recently initiated project, the MOONRISE payload shall be developed towards a flight model (FM) to be accommodated on a robotic arm/rover of a commercial lunar lander. For the FM the CotS approach will be maintained as far as possible to reduce costs. Acquired images from external cameras will serve not only for process observation, but also for finding an appropriate site for laser melting and subsequent evaluation of the laser generated objects. For the latter tasks, artificial intelligence (AI) is planned to be used. During the mission received images of the lunar surface and the generated structures shall be processed on ground by AI to support the choice of laser melting sites and the evaluation of the appropriateness of the laser generated samples. For this purpose, there are currently several lunar terrain models including realistic illumination under construction, with which training data (images) for the AI will be generated.

5. SUMMARY

In summary, an Engineering Model (EM) of the MOONRISE payload for a proof-of-concept experiment for M-SLM on the lunar surface was developed and environmentally tested. The dimension of the payload is equivalent to a 1.5 U CubeSat (10 x 10 x 15 cm^3). It has a mass of about 2.7 kg with further reduction potential towards Flight Model (FM) development. The process of M-SLM process was verified in vacuum in the Einstein-Elevator under lunar gravity conditions producing melted regolith spheres with a diameter of about 3 mm by fixed spot irradiation. For verification of the procedure for generation of larger structures, the EM was attached to a robotic arm. By moving this robotic arm, flat rectangular specimens with a size of 20 mm x 20 mm x 4 mm could be generated.

Three follow-on projects have been initiated recently in order to (1) develop the MOONRISE payload towards a FM with accommodation on a commercial lunar lander, in order to (2) apply 2D laser beam deflection techniques for process scaling on a potential follow-on payload and in order to (3) investigate the detailed process of regolith laser melting under lunar gravity conditions in the Einstein-Elevator.

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