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Tests of additive manufacturing and other processes under space gravity conditions in the Einstein-Elevator

Tests von additiver Fertigung und anderen Prozessen unter Weltraum-gravitationsbedingungen im Einstein-Elevator

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Material processing and material transport systems on Earth are designed for Earth's gravity and atmosphere. In order to pave the way for the future colonization of space, production technologies and transport systems are an essential factor in reducing costs and logistical efforts, such as *in-situ resource utilization* (*ISRU*). Laser-based additive manufacturing methods offer the possibility of a production process independent of environmental conditions and a high degree of adaptability to the objects to be manufactured. These and other processes, e.g. for material handling of powder in microgravity, will be investigated in the *Einstein-Elevator* in the future. This paper first describes the possibilities for the investigation of large scientific experimental setups under different gravitational conditions. Subsequently, the requirements for the experiments and an exemplary project sequence are described using the example of the *MOONRISE* project. In addition, first experimental results are presented.

[Keywords: Einstein-Elevator, MOONRISE, additive manufacturing, production and transport systems, space gravity conditions]

Materialverarbeitungs- sowie Materialtransportsysteme auf der Erde sind prozessbedingt auf die Erdgravitation und -atmosphäre ausgelegt. Um den Weg für die zukünftige Kolonisierung des Weltraums zu ebnen, sind Produktionstechnologien sowie Transportsysteme ein essentieller Faktor zur Reduzierung von Kosten und logistischem Aufwand, wie beispielsweise bei der *In-situ Resource Utilization* (*ISRU*). Laserbasierte additive Herstellungsverfahren bieten dabei die Möglichkeit eines von Umgebungsbedingungen unabhängigen Verarbeitungspro-zesses sowie eine hohe Anpassungsfähigkeit an die herzustellenden Objekte. Diese und weitere Verfahren, z.B. zur Materialhandhabung von Pulver in Schwerelosigkeit, werden im *Einstein-Elevator* in Zukunft untersucht. In dieser Veröffentlichung werden zunächst die Möglichkeiten für die Untersuchung großer wissenschaftlicher Experimentaufbauten in unterschiedlichen Gravitationsbedingungen beschrieben. Am Beispiel des Projekts *MOONRISE* werden anschließend die Anforderungen an die Experimente und ein beispielhafter Projektablauf dargestellt. Außerdem werden erste Versuchsergebnisse präsentiert.

[Schlüsselwörter: Einstein-Elevator, MOONRISE, additive Fertigung, Produktions- und Transportsysteme, Weltraumgravitationsbedingungen]

1 INTRODUCTION

For the development of systems required for space flights, journeys in space and the colonization of space, as

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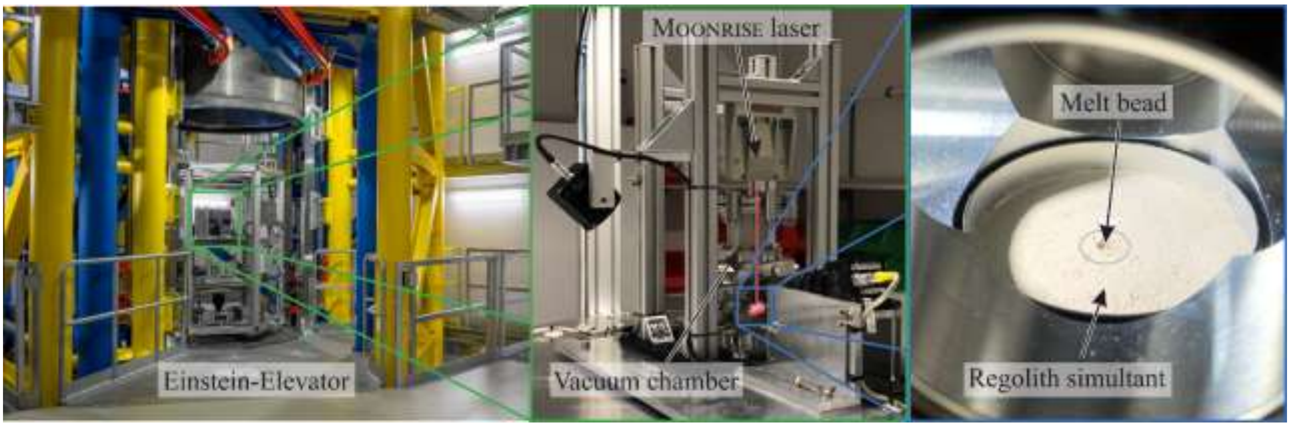

Figure 1. MOONRISE in the Einstein-Elevator, Left: Experimental setup inside the gondola (based on source: LUH/Marie-Luise Kolb). Middle: Flight hardware of the MOONRISE laser system. Right: Melt bead of regolith in the evacuated process chamber

well as also for the investigation of terrestrial phenomena, experiments can be carried out under microgravity in classical drop towers. In the *Einstein-Elevator*, the worldwide unique next generation drop tower of the *Leibniz University Hannover* (*LUH*), these and other gravity conditions can be simulated on Earth for the first time and at a high repetition rate. An example of experiments in the *Einstein-Elevator* is the *MOONRISE* project. The *Laser Zentrum Hannover e.V.* (*LZH*) together with the *Institute of Space Systems* (*IRAS*) of the *Technische Universität Braunschweig* are taking a first step in the processing of Moon regolith by means of the *Mobile Selective Laser Melting* (*M-SLM*) process [Vos18, Ger18]. The aim of the project is to develop a compact payload that operates under lunar environmental conditions (gravity, pressure/vacuum, temperature). With the successful laser melting of regolith under vacuum and Earth gravity, the system tests were continued in microgravity and under Moon gravity in the *Einstein-Elevator* (see Figure 1). This innovative drop tower allows microgravity and other adjustable gravity conditions for up to 300 times a day for 4 s for large experimental setups with a mass of up to 1,000 kg [Lot17, Lot18]. The worldwide unique drive and guidance concept of the *Einstein-Elevator* enables significant progress in research for future space missions and other fundamental questions, from process technology to material transport systems.

Space research will only lead to representative results when performed under comparable gravitational conditions. But the targeted exclusion of the often strongly masking gravity is also an important instrument of modern research for the investigation of tiny terrestrial effects. The classical drop tower concepts available worldwide are not sufficient to meet today's requirements for high repetition rates for statistical investigations and investigations under adjustable gravitational conditions [Lot17]. This gap will be filled by next generation drop towers. In contrast to the conventional complex evacuation of large vacuum tubes, directly driven drop towers enable experiments in small movable vacuum chambers surrounding the experiment. In addition, they are highly automated. The *Einstein-Elevator* is the first system of this new type to be put into operation. No other system in the world is ready for operation. However, similar concepts are being developed worldwide [Koe15, Urb15]. Comparable research environments can currently only be carried out in parabolic flights or on board the *International Space Station* (*ISS*) with immense safety requirements and at high costs.

The paper first gives a description with the essential specifications of the system. Afterwards the general project procedure for future experiments is shown. The design of the experiment setups, the operation of the experiments and the safety regulations are described. As an example for a first successful campaign the project *MOONRISE* is presented and its project procedure in the *Einstein-Elevator* is explained. Finally, a look at further experiments on the horizon is given and a vision for the future of research under space conditions is outlined.

The *Einstein-Elevator* offers scientists worldwide new opportunities for experiments under space conditions on Earth. For the first time, the described system concept provides the adjustability of different gravitational conditions and high repetition rates. The project schedule is lean and offers an open platform for researchers of all subject areas.

2 EINSTEIN-ELEVATOR

The *Einstein-Elevator* at the *Hannover Institute of Technology* (*HITec*) of the *LUH* is a research facility for large-scale experimental setups for scientific explorations in adjustable gravity conditions, including microgravity. In contrast to existing microgravity facilities such as classical drop towers, parabolic flights, rocket missions and space stations, the *Einstein-Elevator* provides researchers with a cost-effective, time saving and readily accessible facility. It offers a high repetition rate, e.g. by avoiding the serious disadvantage of long evacuation times of the free fall tube by hosting the experiment in a vertically movable vacuum chamber, the so-called gondola. The innovative drive and guidance concept of the *Einstein-Elevator* shown in Figure 2 consists of a guided gondola, which is actively driven by a linear synchronous motor. With this innovative drive experiments are feasible in microgravity conditions (µ*g* ≡ 10^{-6} *g* ≈ 0 *g*), which are in main focus, but for the first time tests also can be carried out in the range of 0 *g* to 1 *g* (hypogravity) and 1 *g* to 5 *g* (hypergravity).

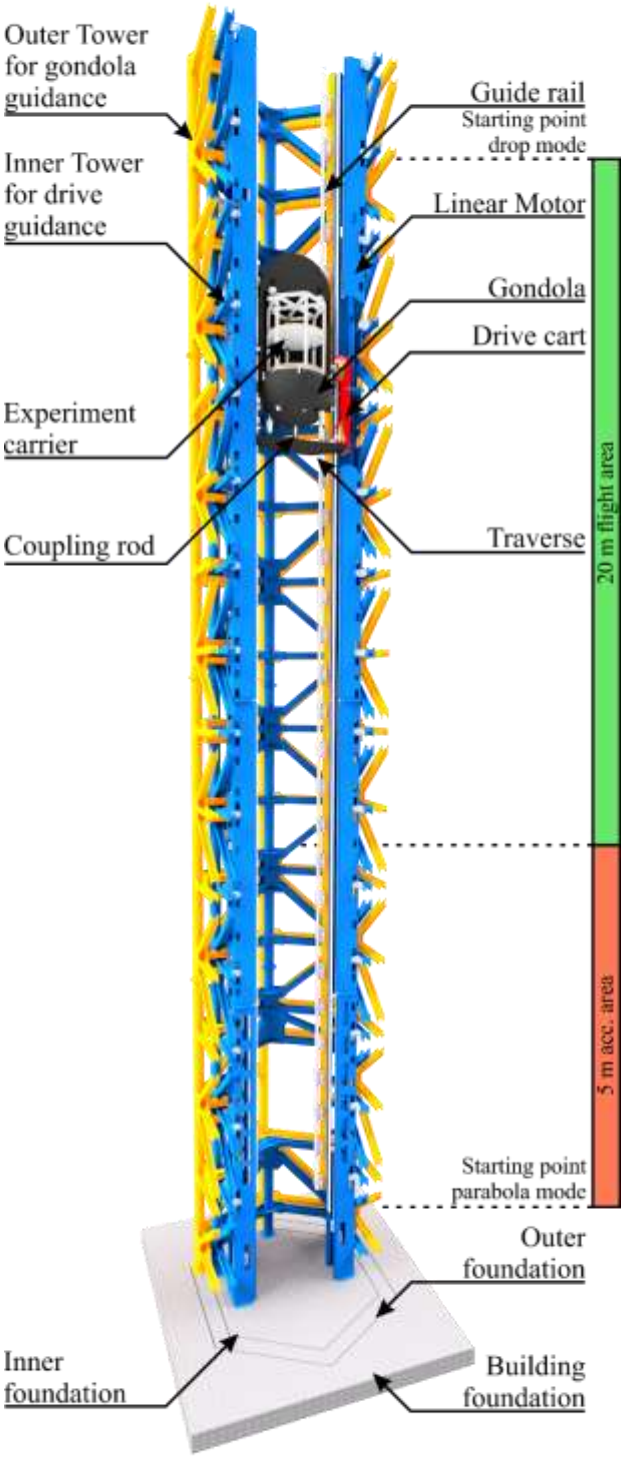

Figure 2. Design of the Einstein-Elevator

2.1 General test procedure

The experimental setup is integrated into a modularly built experiment carrier inside the gondola, which acts outwardly as a drag shield, i.e. a protection against air friction, and inwardly through its inner vacuum as a decoupling against mechanical and acoustic vibrations generated by the guide rollers of the gondola and the drive. The linear drive accelerates the gondola from the starting point for the parabola mode in the loading level with a maximum of 5 *g* up to 20 m/s within 5 m. Subsequently, the drive control system separates the experiment carrier from the gondola floor to a defined distance (currently about 50 mm, which will be significantly reduced in the future) and maintains this distance during the entire parabolic flight so that the experimental setup is exposed to weightlessness. At the end of the flight, the gondola is brought closer to the experiment carrier again and safely decelerated by short-circuiting the motor elements, which now act as eddy current brakes. Additionally switchable eddy current brakes support the braking due to their poorer efficiency during braking in contrast to active acceleration. The gondola comes to a standstill again at the loading level.

In addition to the parabola mode, test executions can also be performed in drop mode. For this purpose, the gondola is brought to the upper starting position before the test execution using a gantry crane and secured there in a holding device. Deactivating this device releases the gondola from the upper starting position. Braking is done in the same way and as safe as in parabola mode by short-circuiting the drive elements and the supporting switchable eddy current breaks.

For the hypo- and hypergravity two trajectory profiles, the experiment carrier is locked to the floor of the gondola. In contrast to the microgravity profile, the drive no longer controls the gondola around the experiment carrier at a fixed distance, but actively brakes the experiment carrier to the set residual acceleration after the acceleration phase.

2.2 Setup

Unlike conventional drop towers, in which the drop path is fully evacuated, only the gondola is evacuated and travels surrounding the experiment during the microgravity phase. This offers significant time saving when creating the vacuum and hence drastically reduces the experiment preparatory times. Figure 3 shows the experiment inside the opened gondola, while the gondola and the experiment travel in the tower in Figure 4.

In order to guide the gondola and to attach the drive as well as the braking system and the peripherals, a complex steel construction is used. To avoid the transfer of vibrations between the emitting drive and the sensitive gondola, a tower-in-tower design has been implemented with two mechanically not connected towers standing one inside the other for mounting the respective components

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Figure 3. View inside the system at loading level, 1) outer supporting structure, 2) inner supporting structure, 3) gondola, 4) experiment carrier (based on source: LUH/Marie-Luise Kolb)

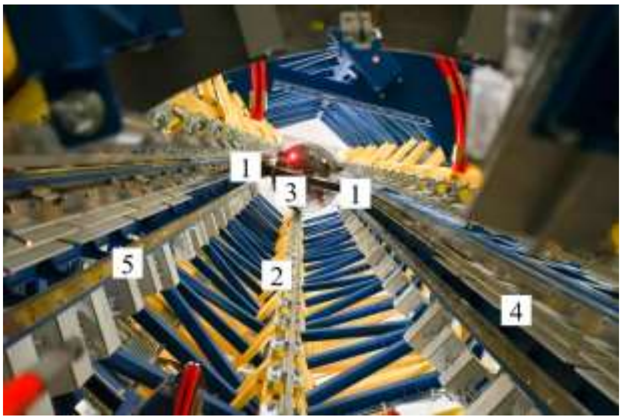

Figure 4. View from below, while gondola and experiment are in motion to the upper reversal point, 1) drive carts: 2) guide rails for gondola guidance, 3) traverse, 4) stators, 5) guide rails for drive guidance (based on source: LUH/Marie-Luise Kolb)

[Lot13]. The two independent towers stand on separate ring wall pile foundations. The only connection between the drive and the gondola is a specially mounted coupling rod, which transfers the vertical feed forces of the two drive carts, while preventing vibrations in a horizontal direction. The two drive carts are connected to each other by the traverse, to which the coupling rod to the gondola is attached centrally in turn. This design effectively minimizes the transfer of vibrations into the experiment carrier and also the excitation of the experiment during the acceleration phase.

The experimental setup is fitted to a modularly built experiment carrier (Figure 5), having a height of 2 m and a diameter of 1.7 m and may not exceed a combined weight of 1,000 kg. The full implemented and commissioned experiment carrier will be balanced by an employee of the *Einstein-Elevator*. This process involves loading the experiment carrier ± 50 g with ballast weights so that the center of gravity is exactly on the axis of the cylindrical experiment carrier. It prevents an oblique throwing or an unintentional movement of the experiment carrier during the microgravity phase.

The configuration of experiment setup and experiment carrier is placed in the gondola for the test execution. Generating a vacuum inside the gondola minimize negative influences on the residual acceleration of the experiment due to the acoustic noise level. However, for this purpose the experiment carrier must be provided with a pressure-tight envelope. Flexibly adjustable or removable intermediate shelves as well as various mounting surfaces are available for the experimental setup. The basic structure of the experiment carrier consists of aluminum extrusion profiles and is compatible with a wide range of connecting elements.

In order to avoid long downtimes between test executions, key processes such as the realignment of the experiment carrier and any necessary vacuum restoration are automated and take place during the cooling phase of the drive elements. Due to Coriolis force, the displacement of the experiment carrier from the center of the gondola's floor is about 5 mm. The recentering is carried out with the aid of a lifting mechanism, which presses a vacuum-sealed

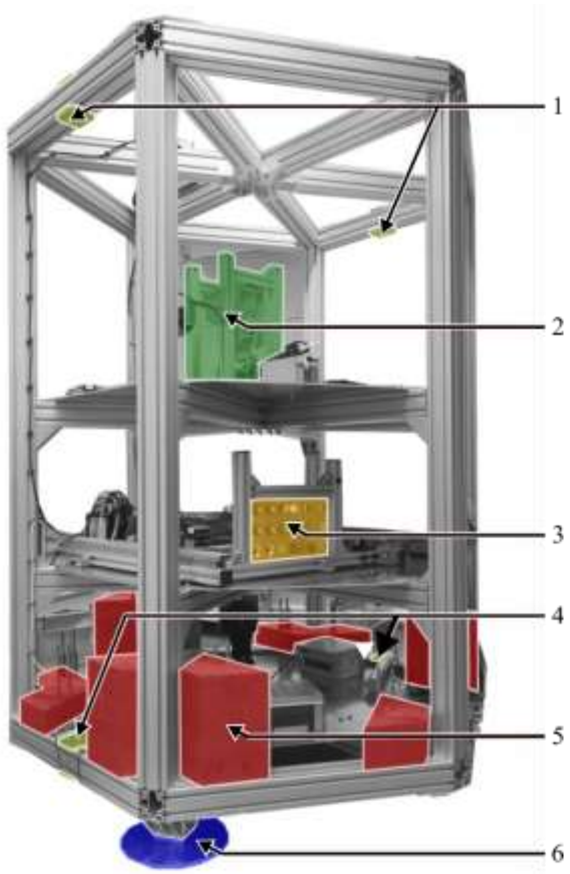

Figure 5. Experiment carrier including the experimental setup of M*OONRISE*, *1) upper centering rods with lifting points, 2)* M*OONRISE-setup, 3) control panel, 4) lower centering rods with integrated power connection, 5) ballast weights, 6) foot of the carrier*

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rod system with ball heads under the conical feet of the experiment carrier from outside the gondola. Vacuum renewal, which may be necessary due to small leaks, is performed by an automated coupling device, which docks to the gondola if necessary and simultaneously opens the vacuum flange of the gondola so that the internal pressure or vacuum can be restored. At the same time as the above processes, the internal batteries are recharged. This interaction achieves a maximum downtime of 4 min after each test execution and enables a repetition rate of 300 test executions per day in a three-shift operation. For extremely time-critical experiments, the waiting time between the test executions can be reduced to less than 1.5 min, provided that it is not necessary to open the gondola or pump up the vacuum as well as the temperature of the drive elements was previously at a level permitted for this purpose. However, after such a fast execution campaign the drive elements require a longer cooling phase. In [Lot17] further design details can be found.

The experiment carrier is equipped with various sensors, e.g. for acceleration measurement in different frequency ranges, as well as large number of interfaces to possible experimental setups. It has a 24 V DC on-board power supply. Inside the gondola, power is supplied via the lower guide cylinders of the experiment carrier and is automatically reloaded during downtimes. As soon as these connections are disconnected, even during the experiment, the internal battery takes over the power supply. At the preparation area the power supply is provided by service lines. In addition, further voltage levels such as 5 V DC and 48 V DC are available.

The data exchange between the control room and the gondola takes place via *optical data couplers* (*ODC*), which optically transmits the communication signal along the movement path of the gondola. Inside the gondola, there is another *ODC*, so that a cable or radio connection to the experiment carrier is not necessary. The data connection is active during the entire test execution so that communication with the experiment is possible at any time.

For the preparation and implementation of the experimental setups, the researchers have access to the *HITec* infrastructure, which among other things offers two preparation areas (Figure 6) and a selection of mechanical and electrical tools as well as two to four workstations in the control room (Figure 7).

Using the experiment carrier infrastructure provided, data communication, power supply and measurement recording are combined in the *carrier control unit* (*CCU*). Furthermore, individual adaptations of the *CCU* are possible for each experimental setup. For example, serial communication interfaces as well as analogue and digital inputs and outputs can be provided.

Figure 6. Two experimental setups can be mounted simultaneously in the preparation area

Figure 7. Control room provides 4 to 6 seats for the system and experiment supervision

2.3 FLIGHT RESULTS/PERFORMANCE

The focus of the test executions is about carrying out experiments in microgravity (μ*g*) conditions. In this type of experiment the duration of pure weightlessness of the experimental setup is 4 s. In addition, the *Einstein-Elevator* offers the possibility to conduct experiments in adjustable gravity conditions in the range of $0\,g < a \leq 5\,g$.

Hypogravity, such as the gravity conditions on lunar (0.165 *g*) or Martian (0.376 *g*) surface, is realized by defined pushing of the gondola after the acceleration phase to the set gravity level in its up and down movement of the parabolic flight trajectory. Recorded acceleration data from sensors near the experimental setup are shown in Figure 8. The duration of the test execution in hypogravity mode depends on the selected profile and has a range of 4.1 s (0.05 *g*) to 12.8 s (0.9 *g*). Figure 9 presents an overview of the duration in different gravity conditions. In [Lot17] equations for the calculation of the profile depending flight duration can be found.

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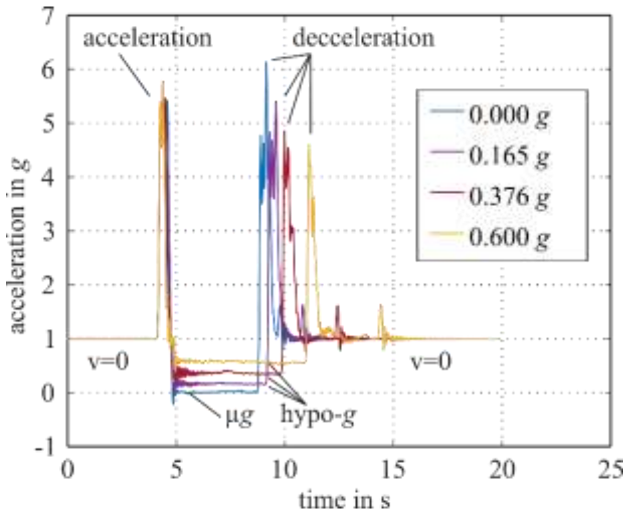

Figure 8. Acceleration curves of selected driving profiles

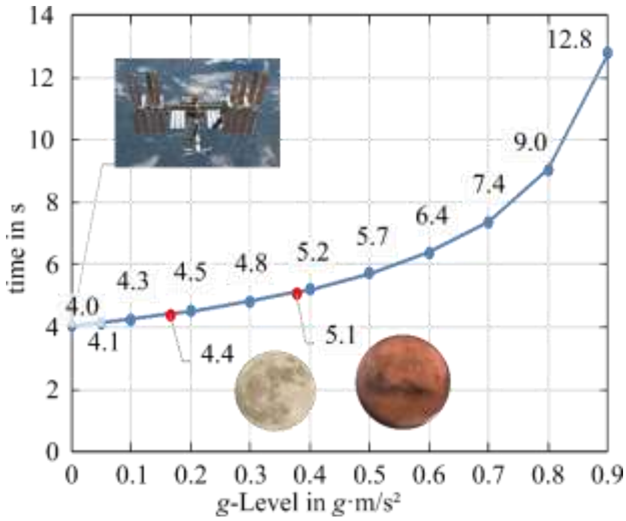

Figure 9. Duration in different simulated gravity conditions in the Einstein-Elevator

Hypergravity, such as the acceleration during a rocket launch, is conducted during the acceleration phase of the gondola, which is constantly accelerated with the gravity level to be looked at. After that, the gondola carries out the standard vertical parabolic flight.

Now, no exact statements can be made about the quality of the set accelerations, as some system components are still undergoing further development. For example, work is still required on the vacuum system of the gondola and the experiment carrier must be designed to be low-vibration with a fast vibration decay. The current carrier was used for commissioning the drive. Its use for initial experiments is only a temporary solution. More information on this topic can be found in Section 5.

3 Project schedule/General sequence

The *Einstein-Elevator* is intended to give scientists from national and international research institutions access to a test facility for adjustable gravity conditions for large-scale experimental setups. Research topics from a wide range of disciplines can be investigated as long as they fit into the gondola and meet the safety standards. As an example for a typical project setup, the following describes the schedule of the project *Moonrise*, a project of the *LZH* in cooperation with the *IRAS*.

3.1 Organizational details

The researchers firstly contact the management of the *Einstein-Elevator* with their idea. Together, the feasibility is evaluated. Does the planned setup fit into the gondola or the experiment carrier, is the time in the needed *g*-level sufficient, which possible accelerations may occur before the start (alternative: start from top position with less time in flight), can the safety requirements be met? If the result of the evaluation is positive, an offer for the support and use of the facility is prepared. This is usually already required during the application procedure for the projects and is based on the project schedule of the respective experiment, which the management of the *Einstein-Elevator* also assists in preparing. After approval of the respective project, the technical and organizational steps for implementing the project are discussed. The preparation of the experimental setup is done in close cooperation between the technicians of the *Einstein-Elevator* and the scientists or their assigned technical staff. Depending on the project, the experimental setup is installed on site in an existing carrier or comes to the facility as a prefabricated structure in an own carrier. Therefore the requirements will be already considered during the evaluation and offer phase. Days before the test execution starts, the *CCU* with telemetry, control PC and other infrastructure is integrated into the carrier, the carrier is balanced and the operators of the *Einstein-Elevator* carry out a final safety check. Minutes before starting the flight procedure the carrier is integrated into the *Einstein-Elevator* by the operating team. The tests are carried out under the permanent control and supervision of an *Einstein-Elevator* employee. Following the implementation, the experimental setup is removed from the gondola, prepared for transport to the research facility. The telemetry data is evaluated afterwards by an *Einstein-Elevator* employee. Finally, joint publications of the research results are prepared and the financial management of the project is completed. More details can be found in a user manual, which will soon be made available to potential interested parties on request.

3.2 Safety details

When operating the system, a distinction must first be made between personal safety and machine safety. Both risk areas can be caused by improper use and malfunctions of the system as well as by malfunctions of the experiment or its operation. The following safety aspects must be considered for the experiment carrier or the experimental setup in order to prevent damage to man and machine.

- Mechanical load capacity
- Electromagnetic compatibility
- Electrical safety

Mechanical loads can vary considerably during the operation of the *Einstein-Elevator*. According to the acceleration values shown in Table 1, each component of the gondola, the experiment carrier and the experimental setup shall be designed to these accelerations. The experimenters are liable for their setups.

Table 1: Acceleration during different operating states

Operating state	*Acceleration and direction*	*Description*
Normal operation	*5-6 g (downwards)*	*Normal acceleration phase and normal service brake*
Emergency stop	*10 g (both up and down)*	*In the event of an unscheduled stop during the acceleration phase or complete control failure in the downward movement*
Start from Top-Position	*1-1,5 g (downwards)*	*During crane travel and at top position at standstill*

The experimental setups must withstand 10 *g* in the case of an emergency stop without causing damage to the support, the gondola or other parts of the system by parts flying around. In addition, the following points regarding the mechanical setup shall be considered when designing the experimental setup:

- Avoiding the installation of vibration generating components such as fans or motors
- Avoiding the use of thin-walled structures without support such as intermediate floors
- Using the installation of mechanical structures that are as rigid as possible
- Avoiding the presence of sharp edges (risk of injury, chafing of cables)
- Avoiding the exposition of electrical contacts
- Avoiding the hanging around of lines of any kind (for example electric, hydraulic, pneumatic etc.) to avoid disturbing vibrations
- Using the encapsulation of combustion processes, liquid circuits, etc. to prevent leakage into the experiment carrier or the interior of the gondola

Furthermore, when implementing/modifying the experimental setup, care must be taken to ensure that assembly material (e.g. tools, screws, etc.) is always placed outside the experiment carrier on the laboratory benches during experiment preparation. This prevents accidental leaving in the carrier and the resulting damage during the test execution.

In addition to the mechanical loads, a number of things must be taken into account in the electrical installations of the experimental setups to ensure both electromagnetic compatibility and general electrical safety. The linear drives of the *Einstein-Elevator* generate strong magnetic fields, which could possibly influence the experimental setup. For experiments that are sensitive to magnetic fields, an appropriate Mu-metal shielding should be used around the critical areas. A measurement of the occurring magnetic fields spatially resolved is planned. The following points must also be observed:

- Using of enclosure and shields for sensitive components as well as twisting of electrical lines
- Using of non-magnetic installation materials
- Avoiding the creation of conductor or ground loops
- Placing the lines for power supply, data transmission and control commands in separate cables

During the final safety checks, the mechanical and electrical properties are inspected together with the experimenters. Subsequently, a release for use in the facility is granted and the experiment carrier with the experimental setup is brought into the gondola for the test execution.

4 Example: Moonrise

The vision driving the *Moonrise* project is to bring additive manufacturing to the Moon. Moon dust, the so-called regolith, shall ultimately be processed directly on the lunar surface, reducing the need to carry building material from Earth. This is called *in-situ resource utilization* (*ISRU*) and can significantly reduce transportation costs– the key for the realization of a lunar village.

Among the main challenges for successful additive manufacturing on the Moon are altered gravitational and atmospheric conditions. The *Einstein-Elevator* provides infrastructure that is very well suited for testing the process in lunar conditions as the gravitation can be adjusted during the campaign. The atmospheric conditions on the Moon can be adequately simulated by a vacuum. Therefore, a vacuum chamber was designed to accommodate the powder material during the experiments. Figure 10 shows the vacuum chamber along with the *Moonrise* laser system, the high-speed camera, lighting and the regolith simulant powder. The use of two of these chambers along with a quick insertion mechanism allowed for an efficient

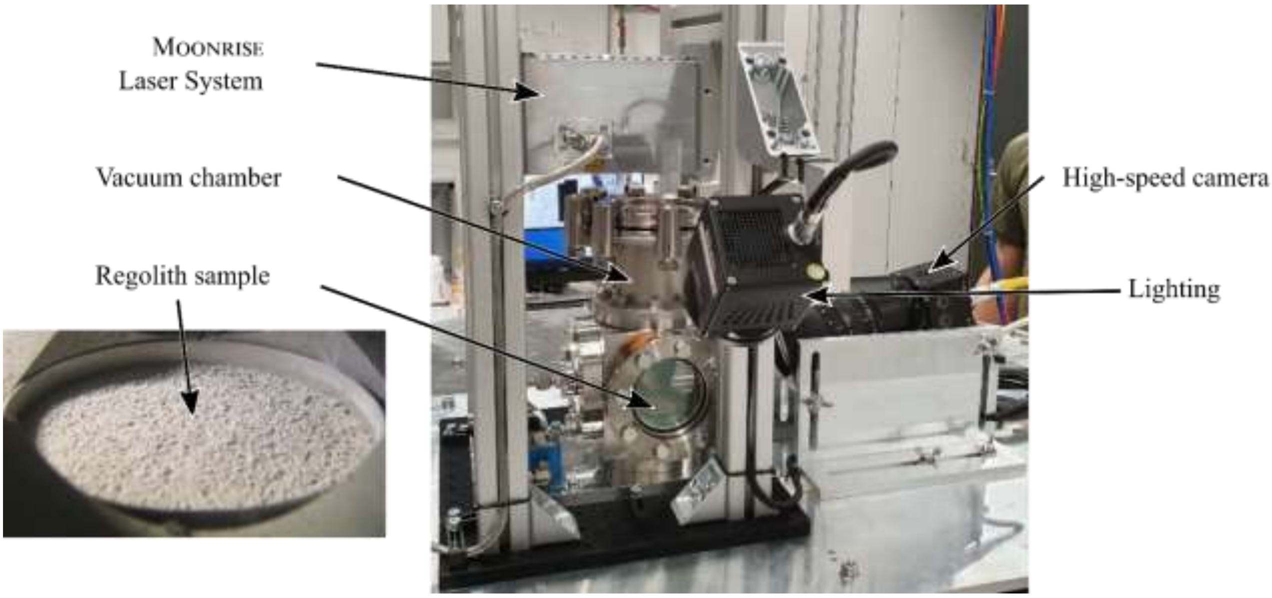

Figure 10. Experimental setup for laser melting of regolith under lunar conditions in the Einstein-Elevator

reloading of the experiment carrier in between flights. The powder material was placed inside a metal vessel (left), that could be inserted into the chamber and was fixed during the experiments using small magnets. Before each experiment, a pressure of 10^{-2} mbar was generated and the powder was compressed with a defined force of 60 N that was homogeneously applied from above.

The powder used in the laser melting experiments is a regolith simulant developed and manufactured by *IRAS* at *TU Braunschweig* [Lin20]. It reproduces the properties of real lunar soil whose availability for experiments is obviously limited. The simulant contains basalt and anorthosite, which are the common constituents of the regolith on the Moon, even though the composition varies depending on the exact location. The largest grains in the simulant have a diameter of 2 mm whereas the average diameter is significantly smaller with 87 µm, reflecting the actual grain size distribution of regolith on the Moon. Before the experiments, the powder was dried at 700 °C for four hours to ensure low moisture content which even after drying is higher than on the lunar surface.

4.1 FLIGHTS: EARTH GRAVITY, MICROGRAVITY, LUNAR GRAVITY

The goal of the investigations was to understand the process of laser melting of regolith under different gravitational conditions. Besides the experiments carried out under lunar gravity of 0.16 *g*, laser melting was also tested under 0 *g* in the *Einstein-Elevator* and under 1 *g* conditions in the laboratory.

In total, 6 flights under 0 *g* and 7 flights under 0.16 *g* were evaluated to detect random influences with the *Einstein-Elevator*. An example of the motion profile of the gondola and the drive is shown in Figure 11. For the displayed measurement 2020-03-03UTC09-13-39 the 0.16 *g* profile was performed. The most important flight parameters can be seen: Firstly, it was accelerated with about 5 *g*. Secondly, the maximum speed is significantly lower than 20 m/s, as it would be the case with the 0 *g*-profile (20 m/s). Thirdly, the maximum height is about 27 m, which is quite similar to the 0 *g*-profile. And fourthly, the deceleration at the end of the test procedure is also about 5 *g*.

The evaluated flight curves provide an initial overview of whether the test procedure basically corresponds to the planned profile. Accelerometers in the experiment carrier allow a better evaluation of the results. These are installed near the experimental setup and can give a statement about the achieved quality of the set profile. Two selected flights, one under 0 *g* and one under 0.16 *g*, are shown in Figure 12. The time curve of the measured acceleration of

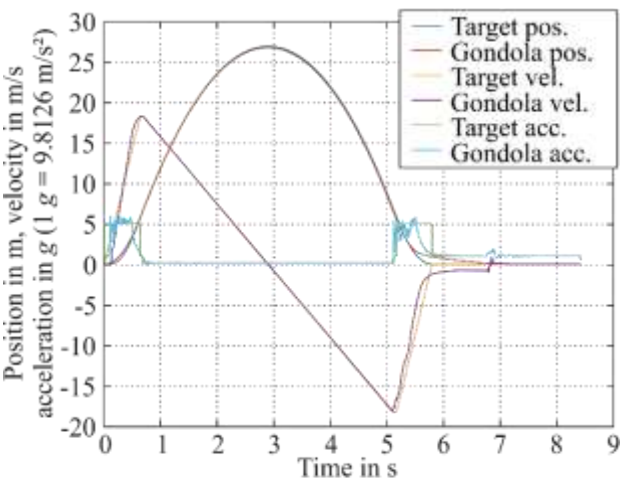

Figure 11. Position, velocity and acceleration of the gondola during flight (Moon-g: 2020-03-03UTC09-13-39)

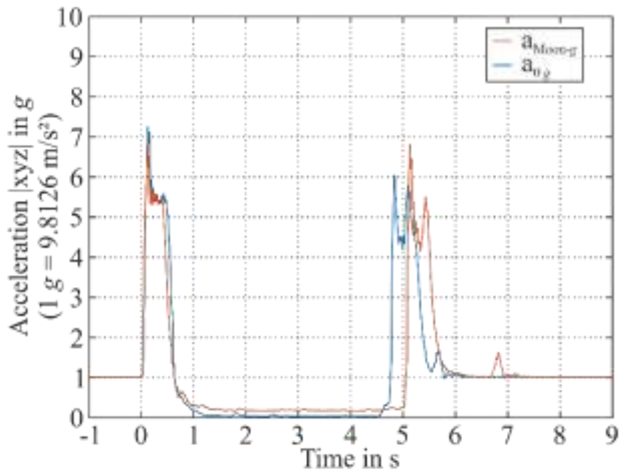

Figure 12. Acceleration |xyz| measured at Experiment Carrier during Flight (Moon-g: 2020-03-03UTC09-13-39, 0 g: 2020-03-10UTC08-58-01))

all three axes combined in the resulting vector |xyz| is shown. The recognizable signature of the acceleration and deceleration phases can be seen. In addition, the difference in the time duration of the set acceleration profiles is also visible. Furthermore, the set acceleration can be seen. A precise evaluation of the achievable accelerations will be published at a later date, since, as previously noted, some systems are still under development. More about the further steps can be found in Section 5.

4.2 Results

In order to allow a comparison between the samples produced in 0 *g*, 0.16 *g* and 1 *g*, the process parameters aside from the gravitation were kept identical. The irradiation time was 3 s such that the laser melting started right at the beginning of the respective gravity condition and stopped before the experiment carrier was decelerated. In this way, the cooling of the sample after melting still took place for about one second before the gravitation changed. The laser power applied was 105 W. Figure 13 shows the laser melting of regolith under lunar gravity at different times during the experiment. When the laser just turned on, only a small sphere of molten material is formed and lots of particles are ejected from the process zone. As the sphere grows, the process stabilizes. The material finally cools after the laser is switched off. It can be taken out of the process chamber after the gondola is opened and the chamber is withdrawn.

The samples produced were analysed in different ways. They were measured geometrically and also analysed in the computer tomograph (CT scanner). Figure 14 shows a CT scan of a regolith sample that was laser melted under lunar gravity. Large and smaller pores can be seen, leading to a relative material density of around 50 %. The difference between the samples that were manufactured under the selected gravity conditions is

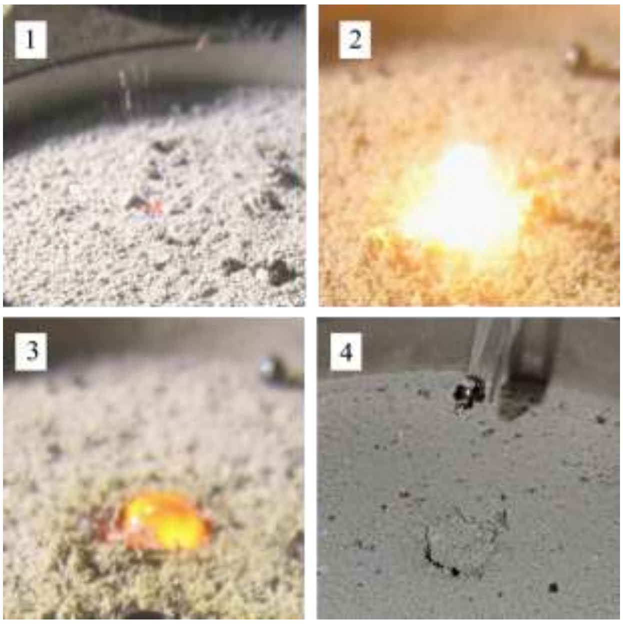

Figure 13. Melting of Moon regolith, 1) Melting process starts with some particles being ejected. 2) A sphere of molten simulant grows and 3) cools. 4) Sample after the process

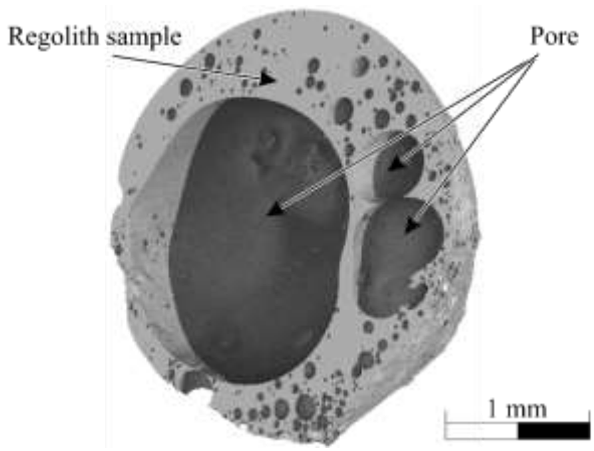

Figure 14. CT-scan of sample laser melted under lunar gravity

analyzed in a different article that is in the review process right now.

5 Next steps/next projects/Visions

In the long term, the facility is to be made available to scientists worldwide. The necessary concepts and personnel capacities are currently being developed. In addition to the technical requirements, for which a user manual is being prepared, a user regulation with the establishment of the necessary committees is also in progress. A scientific proof of the achievable qualities of the facility is also in preparation. For this purpose, a campaign will be flown with international partners and the achievable µg quality will be determined with sensors already successfully used in space. From this point on, the accelerations recorded during the individual campaigns will be made available for detailed evaluation.

Although the *Einstein-Elevator* is already in operation, some systems are still under development. These include an experiment carrier that meets the most diverse requirements with regard to the lowest possible residual accelerations, the lowest possible magnetic fields, vacuum suitability and others. These carrier structures are being developed as part of a project launched in August 2020. Some drive parameters are also adjusted, whereby a reduction of the defined distance of the experiment carrier above the gondola floor during microgravity flight can also be aimed at. This will increase the duration of weightlessness and the capacity of the experiment carrier.

In addition to the preparations for making the facility available to external users and the further development of the facility and experiment carriers, a number of scientific projects from the *LUH*'s own environment are also being prepared. In the future, the *Einstein-Elevator* will be operated together with colleagues from the *Institute of Quantum Optics* with whom it was developed. Accordingly, two thematic areas will be in the focus: production technology for research into new techniques for use under new operating conditions, and quantum physics for research into fundamental questions with the aim of developing more precise Earth measuring sensors or for new time standards, for example. For additive manufacturing, several projects with a focus on laser-based processes are currently being applied for. In addition to the production technology issues, further projects from the field of mechanical engineering are being planned. The declared aim is to establish a center for research under space conditions.

6 SUMMARY

Research under environmental conditions such as those prevailing in space, on the Moon, on the planets of our solar system or other celestial bodies is an essential component of the intended colonization of space. The *Einstein-Elevator* is the world's first to enable experiments under adjustable gravitational conditions on Earth. In addition, the repetition rate and thus the efficiency of the experiments is drastically increased compared to other systems. The organizational process of the experiments and the support possibilities of external researchers are shown and the personnel capacities for a smooth execution of the campaigns are being established. Due to the high degree of automation and the few necessary manual work steps, the safety standards are relatively low. Nevertheless, some requirements and restrictions must be observed. Using the example of the *MOONRISE* project, it was possible to show the procedure of a campaign as well as an insight into the current research on additive manufacturing under space conditions. Further comparable projects are already in preparation. In addition to the implementation of own projects, the facility is constantly being further developed and new experiment carriers with a vibration-optimized structure are being built. In addition, the necessary structures are being set up to enable researchers worldwide to carry out their experiments in the *Einstein-Elevator* in the future.

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