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Novel active driven drop tower facility for microgravity experiments investigating production technologies on the example of substrate-free additive manufacturing

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Abstract

Through the striving of humanity into space, new production processes and technologies for the use under microgravity will be essential in the future. Production of objects in space demands for new processes, like additive manufacturing. This paper presents the concept and the realization for a new machine to investigate microgravity production processes on earth. The machine is based on linear long stator drives and a vacuum chamber carrying up to 1000 kg. For the first time high repetition rate and associated low experimental costs can provide basic research. The paper also introduces the substrate-free additive manufacturing as a future research topic and one of our primary application.

Keywords: Microgravity and hypogravity; Drop tower; Additive manufacturing; Laser beam melting (LBM); Laser metal deposition (LMD); Linear motor

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1. Introduction

Humanity strives towards the population of space and astronomical objects like planet mars or the moon. Production of equipment or spare parts in space or on extraterrestrial bodies will therefore be important (Bollinger, 1987). This requires new processes and technologies, which are useable under weightlessness/microgravity (approx. $10^{-6}\,g$) and hypogravity (below 1 g), such as additive manufacturing. For microgravitational research on earth, sounding rockets, parabola flights and traditional drop towers are available. However, these facilities are cost and time intensive. Hypogravity cannot be established in large scale for use in scientific research on earth until today. The consideration of production processes in space or under extraterrestrial conditions requires a high number of test executions and a continuous modification of the experimental setup. For a better knowledge of process details under these unusual conditions, a machine had to be designed with a high repetition rate and good accessibility for experiments at low costs.

The current development in space industry leads to an increasing demand for micro- and hypogravitation research facilities and, in particular, a higher throughput

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of experiments with the installed drop towers around the world. The current techniques are time intensive and increase the operating costs. For an increase in capacity and microgravity quality, as well as for the realization of hypogravity various concepts are discussed (Könemann et al., 2015; Urban, 2015).

The presented machine *Einstein-Elevator* is an ambitious enhancement of a traditional drop tower. By the use of a new drive technology based on linear motors in combination with a novel control and guidance concept an actively driven test sequence becomes possible. Linear motors accelerate a moveable vacuum chamber holding the integrated experimental setup to the necessary flight speed and compensate for the occurring air and rolling resistance during the subsequent free fall (microgravity) or a modified vertical parabolic flight curve (hypogravity). Deceleration is realized via the drive and eddy current brakes. Due to this automated concept, the repetition rate of the test sequence is greatly increased.

All manufacturing processes on earth involve gravity. Examples are chips dropping downwards during milling and melt flowing to the lowest point during casting. Other processes are for instance laser cutting or laser beam welding with gravity-influenced solidification. In case of additive manufacturing under gravity, a substrate is always necessary. Under microgravity and for the use in hypogravitation, each of these mentioned processes has to be adapted. Substrate-free additive manufacturing will be used to describe the possibilities for future investigations of production processes under microgravity.

This paper focuses on a new machine to analyze production processes under microgravity conditions on earth. It presents in Section 2 the development of a unique machine. Section 3 introduces the substrate-free additive manufacturing focused on the use in microgravity as a new production process and explains its challenges. The integration of new processes and technologies into the novel facility *Einstein-Elevator* takes place in Section 4.

2. Microgravity research with high repetition rate

Research under microgravity on earth can only be realized during free fall in vacuum. In order to extend the duration of free fall, it can also be executed as a parabolic flight in sounding rockets, airplanes and drop towers. In a traditional drop tower, an unguided free fall takes place. Using a catapult, for example, enables a vertical parabolic flight. As a result, the duration is doubled compared to free fall by dropping.

Traditional drop towers with a vacuum chamber for the whole trajectory of the falling experimental setup have the disadvantage of low repetition rates due to high evacuation times. They have long recovery times after a test execution. This results in repetition rates of 2–3 experiments per day, which leads to expensive campaigns for experiments that require statistical analysis (Urban, 2015).

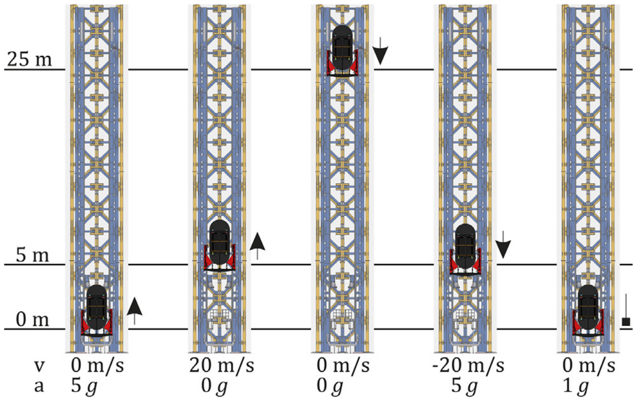

Fig. 1. Movement of the experimental setup in the *Einstein-Elevator*: Actual position, direction of motion, velocity and acceleration.

The function of the *Einstein-Elevator* involves a high degree of automation for the realization of a high repetition rate, as shown in Sections 2.1 and 2.2. The unique feature is the intended repetition rate in combination with a high microgravity quality for large experiments as described in Sections 2.3 and 2.4 with the necessary steps.

2.1. Function of the Einstein-Elevator

In the *Einstein-Elevator*, experiments with a mass of up to 1000 kg, a diameter of 1.7 m and a height of 2 m are to be performed for 4 s in microgravity up to 100 times per day (Lotz et al., 2014; Lotz et al., 2017). The experimental setup is placed in a vacuum chamber, a gondola, that is hardly larger than the setup, which saves a significant amount of time while producing the vacuum atmosphere required for the test execution. The movement of the gondola and the experimental setup is shown in Fig. 1.

Two linear synchronous motors with an output power of approx. 5 MW accelerate this gondola within 5 m to 20 m/s. Subsequently, the experiment carrier is released from the gondola floor and flies autonomously up and down over a distance of 20 m. During the free fall sequence, the drive balances the occurring air and rolling resistance of gondola and guides and keeps the distance between the gondola floor and the experiment carrier constant. After touchdown, the drive and eddy current brakes decelerate the experiment carrier and gondola together to a standstill. In preparation for the next test execution, an automatic alignment device centers the experiment carrier in the gondola without opening it. As an advantage, the vacuum is maintained. The worldwide unique basic setup allows for this automated process for the first time.

2.2. Basic setup

The system is designed for automated operation at high repetition rates and at the same time very low residual acceleration or high microgravity quality as illustrated in Fig. 2a. The design aims to transmit as few vibrations as

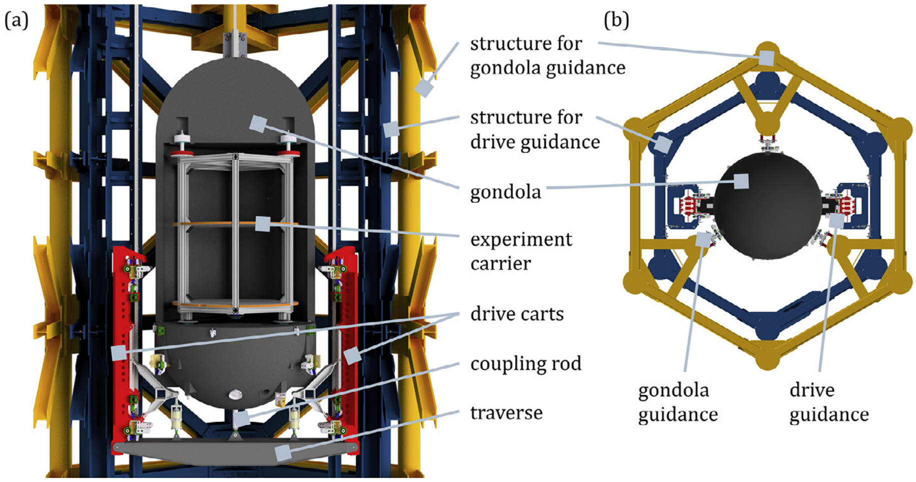

Fig. 2. Basic setup of *Einstein-Elevator's* components: (a) cross section, (b) overview.

possible by external influences, such as drives, guide elements and other mechanical components, to the experiment in order to achieve the highest possible microgravity quality.

For vibrational decoupling, two independent structures divide the frame of the system. Fig. 2b shows the tower-in-tower design that separates the drive and the gondola. Both towers with a total weight of 170 t are independent at their entire height of 36 m. In addition, bored piles with a length of 12 m support their separated circular foundations. The outer tower carries the guides of the gondola and the inner one the drive and drive carts' guides.

Two drive carts realize the high drive forces and compensate for occurring air and rolling resistance in the area of the free-flying experiment carrier. Roller guides steer both individually. The drive requires six rows of primary parts in the acceleration area and two rows in the area of resistance compensation. Linking of the two drive carts is realized by a traverse.

The traverse connects both drive carts to equalize small differences in position. An integrated spring shock absorber additionally provides restoring forces, so that the position differences of the two carts do not rise unlimited. The transmission of the feed force via the traverse in the direction of the gondola takes place by means of a coupling rod. The coupling rod is mounted articulated at both ends. This articulated attachment ensures that no horizontal vibrations are transmitted from the emitting drive to the gondola with the inserted sensitive experiment.

The gondola with aerodynamically optimized hemispherical top and bottom is made of carbon fiber reinforced plastic to save weight and comprises the vacuum chamber that carries the experimental setup during the test execution. Automated couplings connect the gondola to the vacuum pump and the power supply for shortest possible downtimes. The guide of the gondola extends mechanically optimized on three sides. Due to the unique concept, a vibration emitting release mechanism is not necessary. The experiment carrier is unconnected on the gondola floor during acceleration phase, lifts automatically in separation phase by reducing gondola speed, and then flies completely free within the gondola. The carrier achieves a rapid vibration decay during the free-flying phase with its rigid design and additional absorbers, when needed. Additional rods prevent a strong drifting or twisting of the carrier by bumping against damper surfaces, when exceeding projected limitations. In addition, damping elements in the gondola limit the forces occurring during the touchdown of the experiment carrier on the gondola floor just before and while braking.

Short-circuiting the drives and using additional eddy current brakes decelerates the drive carts and the gondola fail-safe at the end of a test execution. After the system has come to a standstill, an automatic alignment system takes over the positioning of the experiment carrier in the gondola center by a lifting system underneath the gondola. Due to non-uniform mechanical deformations of the gondola floor as well as due to the Coriolis force, a maximum position deviation of the carrier of up to 50 mm can occur and automatically be corrected after each test execution.

The experiment carrier is similar to a shelf system. The individual floors hold the experiments and the necessary infrastructure, such as batteries for power supply and telemetry. Section 4 shows details on the structure of the experiment carrier. A pressure-tight cover seals the experiment carrier for use in the vacuum atmosphere of the gondola.

The functions of the specifically developed measuring and communication system are the contactless position detection of the fast moving gondola and the precise distance measurement between gondola and experiment carrier. The measured values of these sensors are to be made available to the drive control unit (DCU). Furthermore, data communication between the experimental setup and the control room is realized as shown in Fig. 3.

The position measurement (PM) of the gondola along the max. 30 m long travel path takes place on the two drive carts with an accuracy of 10 μm. Three laser triangulation

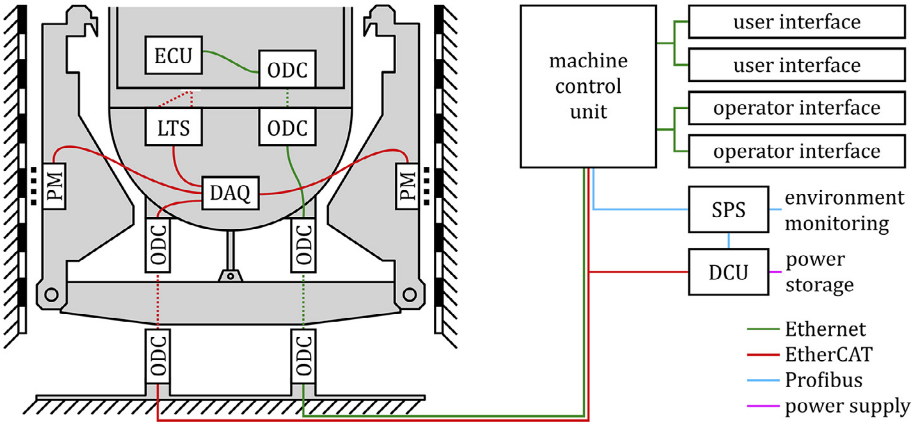

Fig. 3. Schematic of *Einstein-Elevator's* electronical components.

sensors (LTS) with a resolution of 3 μm allow the distance measurement between the gondola floor and the experiment carrier's base. The cycle time of the EtherCAT signal via optical wireless data transmission from the gondola's data acquisition (DAQ) to the DCU at the base of the system is 100 μs. The communication system is an integral part of the drive and machine control.

The communication with the experiment control unit (ECU) is provided by the transmission protocol Ethernet and a data rate of 100 Mbit/s. Optical data couplers (ODC) realize both, the communication between the experiment carrier and the gondola as well as between the gondola and control room. This allows a permanent access to the experimental data, which is also suitable for use at high repetition rate.

2.3. Measures for high repetition rate

The high repetition rate of the *Einstein-Elevator* of up to 100 experiments per day represents the unique feature of the system. The novel concept uses a specially installed linear drive and braking system, a partial vacuum and a low vacuum volume as well as a high level of automation for the test execution.

The electrical drive and braking system is permanently linked to the gondola with the experiment in it. As a result, the drive and brake technology is constantly available. No manual operation is necessary for further test executions like in classical drop towers.

The transport of a partial vacuum around the experiment carrier is a major innovation leading to a significant amount of time being saved. The small vacuum volume of approx. 6 m^3 at 10^{-2} mbar allows for a short pump-down time. By integration of an automatic alignment device, the carrier can be positioned for the next test execution without opening the gondola and thus destroying the vacuum. The vacuum is obtained from one execution to the next and can be restored after leaks by an automatic coupling mechanism. In addition, the battery of the carrier recharges via an automatic coupling. Furthermore, there is permanent communication link between ECU and the control room, so no manual access is needed for parameter changes or to download experimental data recorded during the test execution.

If access is necessary for reworking or a change of experiments, the small vacuum volume and the resulting short pumping-down time ensure a high degree of flexibility. The placement of the experiment carrier in the gondola takes place on a ground level without much effort for an additional time saving. With this concept, the repetition rate drastically increases by still offering the same high microgravity quality as in free-flyer systems (Lämmerzahl and Steinberg, 2015).

2.4. Measures for high microgravity quality

Free-flyer systems allow residual accelerations in the range of 10^{-5} g to slightly better than 10^{-7} g (Selig et al., 2010; Zhang et al., 2005). The advantage results from low vibration transmission during the free fall at a small relative speed between the drag shield and the experimental setup in the additional vacuum atmosphere within the drag shield.

In the *Einstein-Elevator* a microgravity quality of $<10^{-6}$ g is intended. For this reason, its conceptual design resembles the previously described free-flyers. The approach is to achieve the lowest possible excitation by external influences in the acceleration phase and a stiff experiment carrier, in order to achieve a rapid decay during the free-flying phase of the vibrations, which are nevertheless introduced. In order to reduce the vibrational excitation of the experiment, it is therefore essential to minimize the vibrational influences on the gondola.

The roller guide of the gondola with its steel rollers is designed based on a machine tool (Lotz et al., 2015). The accompanying precision as well as the separation of the vibration-inducing drive and the vibration-sensitive gondola by the described tower-in-tower construction (see Section 2.2) and the hinged coupling rod reduce the mechanical excitation to a minimum. Further effects considered in the design are the aerodynamic design of the gondola, the necessary vacuum quality, the absence of a releasing-/gripping-mechanism or actuator system within the gondola (Lotz and Overmeyer, 2013) as well as a high-precision drive control via a specially developed high-resolution measuring and communication system, which Section 2.2 shows. The experiment carrier (see also Section 4) allows for extremely vibration-reduced experiments of production processes under microgravity. In the following we will describe challenges in laser additive manufacturing, which is one of the most promising manufacturing processes in space for the future. The described machine will give the opportunity to analyze this process under space conditions on earth.

3. Substrate-free additive manufacturing as a new production process in space

To produce spare parts, tools or even complete devices directly in space, a convenient manufacturing method is required. On earth, laser additive manufacturing enables the economical production of individual metal parts with great mechanical properties (Schmidt et al., 2017; Kruth et al., 2004) and is therefore an excellent opportunity. Furthermore, the material for additive manufacturing in space has to be brought from earth – most weldable metals are compatible (Schmidt et al., 2017) – or new materials found in space have to be used. In first investigations, *Laser Zentrum Hannover e.V.* processed basalt powder within the laser beam melting process (LBM) successfully (see Fig. 4). Basalt has a similar chemical composition as Regolith, which is found on the moon. Therefore, Basalt can be seen as terrestrial counterpart to Regolith and can be used in investigations on laser additive manufacturing in *Einstein-Elevator*.

Parts are manufactured additively from metal powders by laser beam melting (LBM), often called selective laser melting (Rombouts et al., 2006), or by laser metal deposition (LMD) of metal wires or powder (Graf et al., 2013; Toyserkani et al., 2004). During the LBM process, powder is deposited onto a substrate in a first step. In a second step, a computer controlled laser beam selectively scans the powder. This results in melting of the powder and dense consolidation. Subsequently, the substrate is lowered by one layer size before the steps are repeated for each single layer of the part (Schmidt et al., 2017). In the LMD process, a laser beam is focused on a substrate plate, producing a melt pool. Simultaneously, the material is introduced by a powder nozzle or wire feeder and solidifies in a dense track.

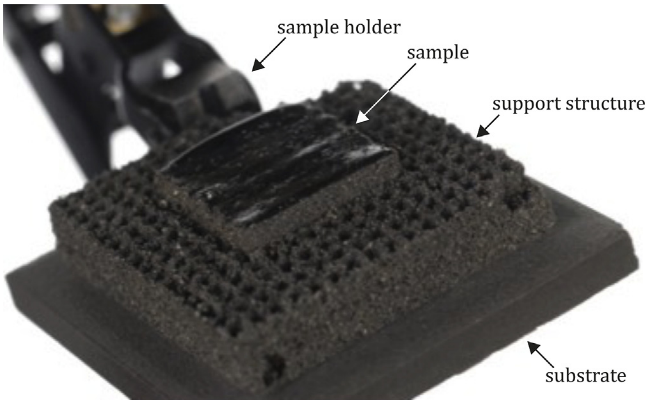

Fig. 4. Basalt sample manufactured by laser beam melting.

For the use in space, the methods have to be modified to cope with the different conditions like microgravity, hypogravity, vacuum or non-vacuum atmosphere. In microgravity, the powder has to be controlled and held together. An open coating device is not possible, because the moving powder could leave the experimental setup when not stopped in the right position. Therefore, another device for powder deposition is required in microgravity and vacuum. Powder transport via ultrasonic or piezo actors is a possible solution. With regard to laser sources, continuous wave or pulsed laser systems need to be tested concerning the process results under microgravity.

To gain more flexibility, additive metal manufacturing in space will be performed substrate-free on a very small spot support or substrate (focal point) instead of a plain substrate (see Fig. 5a). Under microgravity, loose metal powder also brings further difficulties during the process, so the use of metal wires is rational. The building process for laser metal deposition can be started on free formed surfaces, as for example the focal point, in contrast to the selective laser beam melting process where a powder bed is required. The laser metal deposition process works by manipulation of either the part itself around the axis or of the laser and powder nozzle around the part. In space, both opportunities are possible, but the movements and the dynamic effects are restricted to the feeding velocity of the wire and the resulting heat from laser radiation. Special production engineering is required to feed the wire in microgravity, for which friction wheels are useful. Powder has to be fed by gas flow in atmosphere, fed ultrasonically and held by a magnetic field in vacuum.

The next step is to work without substrate or spot support (see Fig. 5b) The biggest challenge will be the deposition of the first melted layers of the part at a certain and stable point. The process itself has to be adapted to microgravity, viscosity of the material, surface tension of melt and parts, as well as heat conduction, which behaves differently in space. Nevertheless, a start spot to begin the additive manufacturing of parts is essential. The part has to be fixed by a special technique during the process, so that all the single layers can be manufactured without uncontrolled variation of the position of the part, for which superconductors or neodymium magnets might be helpful. First investigations can be done by fixing the start point by focusing compressed air streams in the spot or by using a capacitor or a magnetic field for the melted metal wire or powder that forms the first layer of the part.

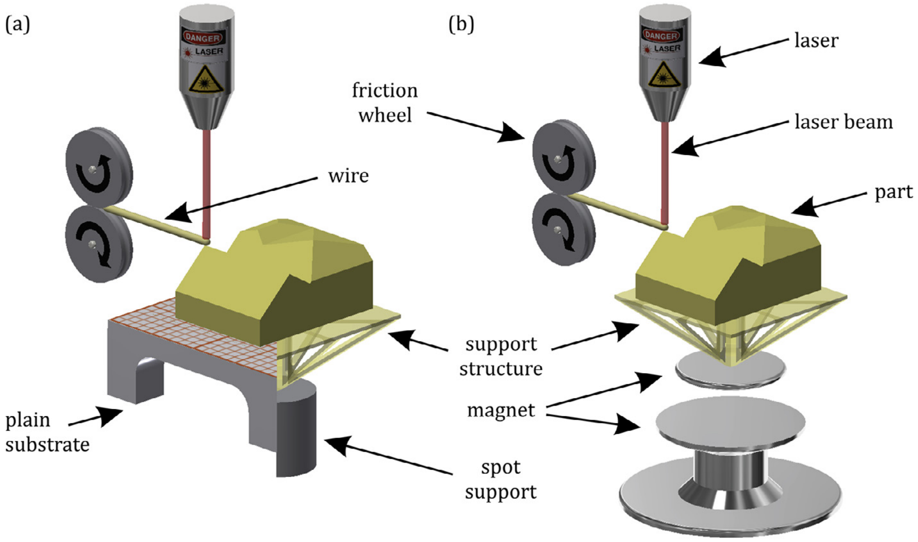

Fig. 5. Additive manufacturing process: (a) with plain substrate or spot support, (b) with spot support or without substrate.

4. Research in the *Einstein-Elevator*

In order to be able to carry out research in the *Einstein-Elevator*, a suitable experiment is to be built. This demands knowledge of the requirements for the experiments, a fitting experiment carrier and providing additional infrastructure.

4.1. Setup of an additive manufacturing experiment

The *Einstein-Elevator* enables microgravity for 4 s. During this time, experiments can be conducted to develop and modify processes on earth for the future use in space. Different laser material processes are possible, depending on the sample size. Micro welding usually uses pulses in the range of few milliseconds. Laser cutting and welding velocities on earth are used in the range of 1–20 m/min, depending on wall thickness of the sample and the laser power. As scan speed for laser beam melting velocities between 50 mm/s up to 5000 mm/s are used, the coating time is 2.5 s on average. Therefore, it is possible to scan a small sample volume of one layer or to recoat when using the LBM process within one experiment. Both steps have to be repeated until the geometry of the complete part is exposed by laser radiation. Laser metal deposition processes, with powder or wire, have deposition rates between 3 and 5000 mm/s.

Moreover, the geometric spatial extensions and weight restrictions of the *Einstein-Elevator* have to be considered referred to the experimental setup. A schematic overview of a possible setup with corresponding weights is given in Fig. 6. For initial tests, the laser metal deposition process with wire is used to exclude powder handling at the beginning. Basic process equipment will be integrated into the process chamber as shown. A needed vibration level for the device and the process is not yet known and has to be determined, but the estimated μg-quality of the *Einstein-Elevator* will over-accomplish the requirements for repeatability and reproducibility of produced results. First tests will be conducted to build up single walls, one track per experiment. Process atmosphere is varying between Argon gas and normal atmosphere. Different process parameters for different single walls were compared to determinate suitable process parameters for laser metal deposition in microgravity. For the investigation of a laser beam melting process, powder handling has to be managed. Possible solutions are transport by ultrasonic or piezo actors as mentioned in Section 3.

4.2. Structure of the experiment carrier

Experiments such as substrate-free additive manufacturing have very specific requirements for research under weightlessness. Different electronics are necessary to control the experiments. A battery provides for their uninterruptible power supply with up to multiple kW during free fall. It operates telemetry, data communication and the experiment control. Video transmission from the inside can be used for process monitoring. For the evaluation of the process observations, the status data around the experiment is important. An inertial measurement unit (IMU) measures, for example, accelerations and rotations. Further requirements are electromagnetic compatibility, alternating magnetic fields, cooling water, process gases or shielding gases for a protective atmosphere. All configurations must meet the space and payload capacity of the experiment carrier.

The experiment carrier is a mounting platform for the scientific payload like the setup shown in Fig. 6. It is designed with flexibly adjustable floors and various mounting possibilities for the experimental setup and its cabling. The design of the setup is optimized with regard to rigidity and fast oscillation decay. The experiment carrier surrounds a pressure-tight cover, which serves to separate

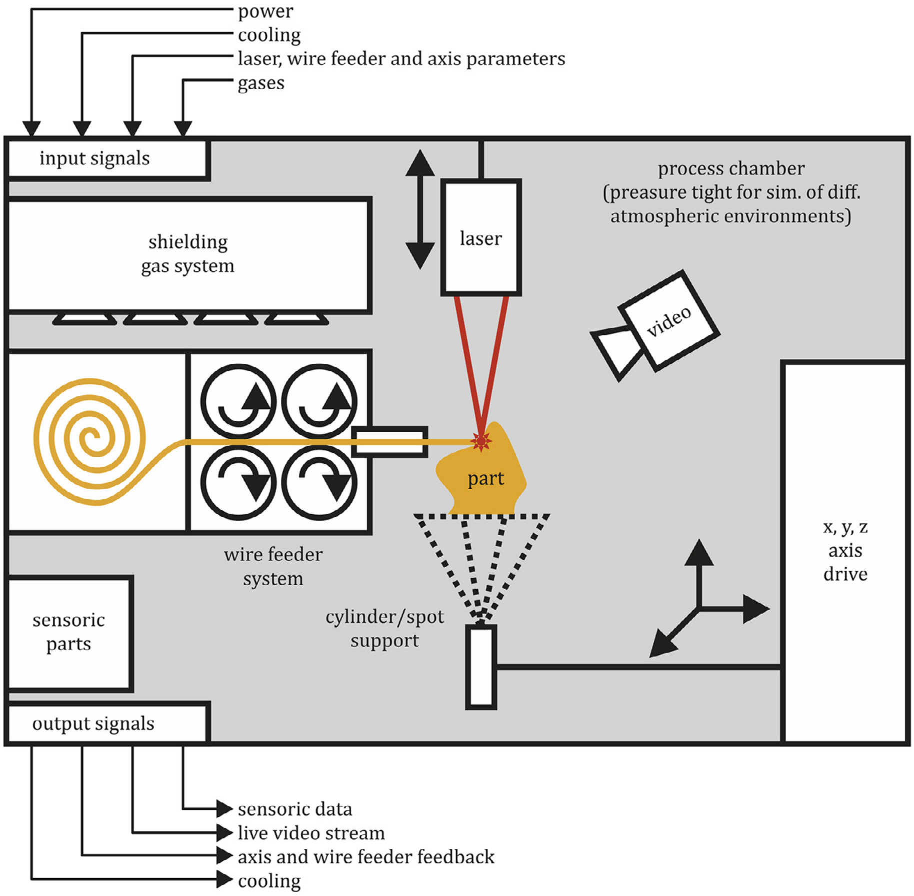

Fig. 6. Setup of the additive manufacturing experiment in a process chamber with an expected weight of 320 kg (2 kW laser system: 75 kg; structures, clamping devices, adapters: 60 kg; analysis and monitor systems: 30 kg; wire feeder system: 25 kg; axis drive: 30 kg; chamber: 100 kg).

the experiment and the vacuum atmosphere in the gondola interior. In addition, the cover may be provided with a shield to keep alternating magnetic fields, for example caused by the drive, from interfering with the experiments. Fig. 7 shows the experiment carrier as a schematic structure and closed with the pressure-tight cover.

The battery, the telemetry and the IMU are housed in the lower part of the experiment carrier. The range above can be expanded as required to maximal diameter of 1.5 m and a height of 1.7 m for the payload. In summation the weight of the assembled experiment carrier is limited to 1000 kg. The amounts are: payload <525 kg, structure and lowest floor 200 kg, pressure-tight cover 250 kg, electronic parts (battery, communication system, ECU and IMU) 25 kg. Finally, the experiment carrier is still to be loaded to 1000 kg and simultaneously balanced, so that the experiment and the supporting structure do not have uneven mechanical loads at the start of the test execution.

For carrying out highly sensitive experiments additional infrastructure, like a preparation area and a control room, is also of great importance. In the preparation area, two workstations are available for the assembly and preparation of the experimental setups before their start. After the final assembly, the experiment carriers are inserted into the *Einstein-Elevator* and then remotely controlled from the control room.

4.3. *Additional infrastructure*

In addition to the experimental area, which is directly necessary for the execution of the tests, the newly built facilities of *Hannover Institute of Technology (HITec)* also provide further required infrastructure (HITec, 2017). The thermally and vibrational stabilized laser laboratories offer a controlled environment. There are also several certified cleanrooms in the building. Workshops provide optical, electrical and mechanical workstations. For the evaluation of the experiments and administrative tasks, the experimenters are also supplied with additional offices as required.

The *HITec* building and the *Einstein-Elevator* are in the phase of final assembly. Most of the parts are mounted, only the gondola is still under construction but its production will be completed soon. The first tests of the facility will take place in spring 2018. It is expected to perform initial operations during the year so that in 2018 the first experiments of internal and external researchers can be conducted.

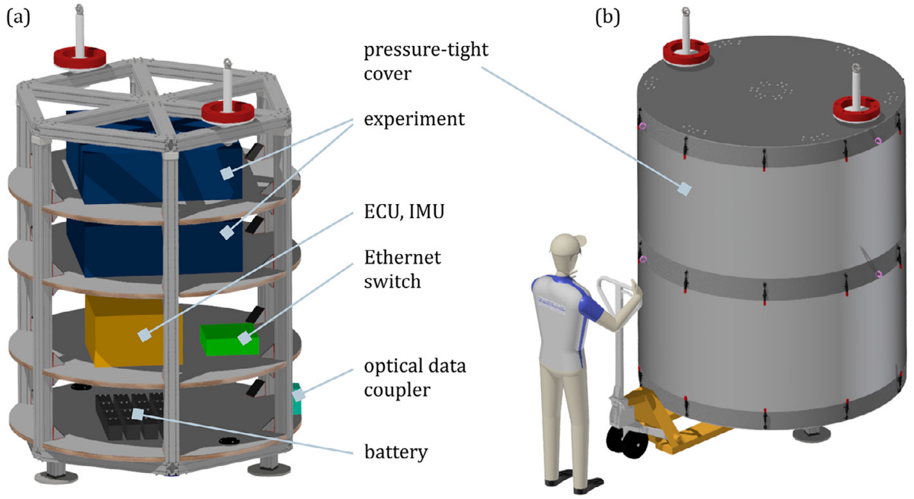

Fig. 7. Schematic of experiment carrier in details: (a) open, (b) closed.

5. Summary and outlook

The commercialization of space is advancing. With it, the demand for suitable production technologies grows. Due to logistical reasons, they are becoming progressively important for use in weightlessness with an increasing distance from the earth. However, so far only little experience is available. To reduce the effort and the associated costs new devices are needed for research under microgravity. The considered process of substrate-free additive manufacturing is of great interest for use in space and can be investigated with the new facility.

The *Einstein-Elevator* offers the infrastructure for 100 experiments per day at a residual acceleration of $<10^{-6}\,g$. Large, complex and at the same time highly sensitive scientific experiments can be investigated. The experiment carrier is equipped with the process chamber, the measuring and control technology as well as the process gases and the further experimental infrastructure to be tested for the substrate-free additive production. The *Einstein-Elevator* is available for research on micro- and hypogravity in *HITec* from 2018 onwards (Einstein-Elevator, 2017).

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