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Einstein-Elevator: A New Facility for Research from µ*g* to 5 *g*

Christoph Lotz[1,2], Tobias Froböse[1,2], Alexander Wanner[2], Ludger Overmeyer[1,3], and Wolfgang Ertmer[2,3]

[1]*Institute of Transport and Automation Technology (ITA), Leibniz Universität Hannover, An der Universität 2, Garbsen, Germany;* [2]*Institute of Quantum Optics (IQ), QUEST Leibniz Research School, Leibniz Universität Hannover, Welfengarten 1, Hannover, Germany;* [3]*Laser Zentrum Hannover e.V., Hollerithallee 8, Hannover, Germany*

ABSTRACT

Increasing efforts to move into space have driven the need for new facilities that are capable of simulating weightlessness and other space gravity conditions on Earth. Simulation of weightlessness/*microgravity* (approximately 10^{-6} *g*) is conducted in different earthbound and flight-based facilities, often with poor availability. Other conditions such as lunar or Martian gravity with their partial Earth gravity/*hypogravity* cannot be performed at a large scale for scientific research on Earth. For multiple Earth gravity/*hypergravity*, simulation centrifuges are available, but they do not allow the possibility of abrupt acceleration changes. To support this wide range of conditions, a new technique is being developed to combine all of these requirements into a single drop tower facility. Currently under construction, the *Einstein-Elevator* of the Hannover Institute of Technology at the Leibniz Universität Hannover is an earthbound tool created for simulating micro-, hypo-, and hypergravity research with a high repetition rate. The facility will be capable of performing 100 experiments per day (8-h work shift), each creating 4 s of microgravity. For the first time, statistics can be applied in experiments under space gravity conditions at favorable costs and short mission times. The Einstein-Elevator offers room for large experiments with a diameter up to 1.7 m and a height up to 2 m as well as weights up to 1,000 kg. To perform larger experiments under different gravitational conditions, it was necessary to develop an innovative drive and guide concept. The Einstein-Elevator will be available for general research under different gravity conditions from 2018 onward.

Key words: Microgravity; Hypogravity; Hypergravity; Einstein-Elevator; Drop Tower; High Repetition Rate; Linear Motors; Vacuum Chamber

Correspondence to: Christoph Lotz
Leibniz Universität Hannover (ITA/HITec)
An der Universität 2
30823 Garbsen, Germany
Telephone: +49 511-762-2291
E-mail: christoph.lotz@hitec.uni-hannover.de

INTRODUCTION

The Einstein-Elevator of the Hannover Institute of Technology (HITec) at the Leibniz Universität Hannover (LUH) is a novel earthbound facility for conducting large-scale scientific experiments under different gravity conditions such as micro-, hypo-, and hypergravity. The repetition rate represents a break-through compared with other drop towers. The facility will be capable of performing 100 tests per 8-h work shift as a result of its unique design and a specially developed drive and guide concept. This paper describes the concept of the Einstein-Elevator and the technical capacities it creates for future experiments.

The current strive toward space and the associated demand for research of new production technologies usable in weightlessness and other gravity conditions such as lunar or Martian gravity have driven the development of the Einstein-Elevator. Additionally, quantum optics experiments conducted at LUH require microgravity conditions to eliminate the masking influence of gravity for the observation of small effects at the quantum level. Currently, investigations on these topics are not feasible, as experiments that need fast access or high repetition rates for statistics are too complicated, too expensive, and allow limited access. Other gravitational conditions such as hypogravity are technically not possible for large-scale scientific experiments.

On a global scale, there are several earthbound facilities available for large-scale interdisciplinary microgravitational research, and they all differ primarily by the duration of the free fall and also by the quality of residual acceleration, payload, and setup dimensions. In Germany, the Bremen drop tower of the Center of Applied Space Technology and Microgravity (ZARM) has been in operation since 1990, comprising a 110 m high-vacuum tube with a free-fall time of 4.7 s (Dittus, 1991). A catapult was added to the system in 2004, creating a 9.3 s free-fall time in a vertical parabolic flight (von Kampen et al., 2006). This drop tower is unique due to its very long free-fall time, which enables interdisciplinary research under microgravity. In the United States, National Aeronautics and Space Administration (NASA) operates two facilities at the NASA Glenn Research Center: the Zero Gravity Research (Zero-G) Facility offers a free-fall time of 5.18 s (Neumann, 2006; Neumann, 2017), whereas the NASA Glenn 2.2 Second Drop Tower (Neumann, 2008) provides for a 2.2 s free-fall time. There are a number of other well-known facilities in the United States, Japan, China, Spain, Russia, and Australia (Fujita, 2009; Wan et al., 2010; Kommunarovich, 2016; Steinberg, 2016; DDT, 2017). All of these facilities are pure drop towers (including drop shafts) with the exception of the aforementioned Bremen drop tower with its integrated catapult. Table 1 presents an overview of the key properties of the largest and most known facilities with respect to the experimental execution and the type of capsule-experiment configuration together with the sources.

In the course of selecting a suitable facility prior to executing the weightlessness experiments, it is necessary to take various properties of the specific facility into account and evaluate them with respect to the experiment's feasibility:

- setup dimensions, payload
- free-fall duration
- residual/maximum accelerations
- repetition rate
- accessibility
- environment/atmosphere
- telemetry
- energy/media
- costs
- safety standards

The main problems with existing drop towers are the long times required for the test series and the associated high cost levels. To perform the number of tests required for statistical measurements, an active accelerated and guided system is needed. However, the guides in such systems generally create vibrations, which in turn influence the precision of the experiments. The Einstein-Elevator therefore represents a revolutionary concept compared with existing earthbound facilities for microgravitational research in drop towers.

This paper describes the concept of the Einstein-Elevator to achieve maximized experimental quality and minimized residual acceleration. Furthermore, the paper provides details of the engineering and technology required to enable a high repetition rate. It also focuses on the technical options available to scientists to enable planning and concept development for future experiments. The paper introduces the experiment carrier implemented in the Einstein-Elevator, describes the interfaces available during experiment execution to the experimental setup, and the details of the infrastructure provided for preparation of the experiment carrier.

To enable economically viable execution of statistical experiments as well as faster accessibility at lower costs across the various fields of aerospace, physics, mechanical engineering, etc., an innovative research

Table 1. Characteristics of various drop towers for research under microgravity. This table is based on data from the following publications: [1] Neumann, 2008; [2] Neumann, 2006; Neumann, 2017; [3] Steinberg, 2007; Steinberg, 2016; Lämmerzahl and Steinberg, 2015; [4] Zhang et al., 2005; Lämmerzahl and Steinberg, 2015; Huang and Mao, 2013; [5] Mori et al., 1993; Koide, 2001; Zhang et al., 2005; [6] Iwakami and Nokura, 2005; Nokura, 2008; [7] Dittus, 1991; ZARM FABmbH, 2011; Lämmerzahl and Steinberg, 2015; [8] Lotz et al., 2014.

Name of facility		NASA Glenn 2.2 Second Drop Tower	Zero Gravity Research (Zero-G) Facility	Micro-gravity Drop Tower	Beijing Drop Tower	Drop Shaft Facility	Drop Exp. Facility	Bremen Drop Tower	Einstein-Elevator
Research institution		NASA	NASA	QUT	NMLC	JAMIC	MGLAB	ZARM	HITec/ LUH
Country		USA		Australia	China	Japan		Germany	
Time in free fall in s		2,2	5,18	2,0	3,5	10	4,5	4,7 / 9,3*	2 / 4*
Free fall distance in m		24	132	20	60	490	100	110*	20*
Minimal residual acceleration		10^{-3} *g*	10^{-5} *g*	10^{-4}-10^{-6} *g*	10^{-3}-10^{-5} *g*	10^{-5} *g*	10^{-5} *g*	10^{-6}-10^{-7} *g*	<10^{-6} *g*
Maximum deceleration		15-30 *g*	35-65 *g*	15-20 *g*	8-12 *g*	8 *g*	10 *g*	40-50 *g*	5 *g*
Repetition rate per day		12	2	15-20	2-4	2-3	1-2	3	100
Experiment payload in kg		$487^C/159^E$	$1130^C/455^E$	150^E	630^C/ 90^E	5000^C/ 500^E	1000^C/ 400^E	$500^C/400^C$* $264^{ES}/221^{EL}$ /$161,5^{ES}$*	1000^C/ 515^E
Experiment	Ø/☐	960 x 400^E	Ø1000^C/ Ø970^E	Ø800^E	Ø850^C	Ø1800^C/ 870 x 870^E	Ø900^C/ Ø720^E	Ø800^C/Ø700^E	Ø1700^C/ Ø1660^E
Dimensions in mm	height	840^E	4000^C/ 1600^E	$1500^C/900^E$	1000^C	7850^C/ 918^E	2280^C/ 885^E	2107^{CL}/ 1341^{CS}* $1718^{EL}/953^{ES}$	2000^C/ 1790^E
Capsule-experiment configuration		DS	VC	DS	DS is VC	DS is VC	DS	VC +optional FF	comb. of DS, VC, FF
Source		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

DS: drag-shield, VC: vacuum-chamber, FF: free-flyer, ^{C}: capsule, ^{E}: experiment, ^{L}: long capsule, ^{S}: short capsule, *: catapult, **: closed 2010.

environment is required. The newly built facility presented in this paper offers a high repetition rate with over 100 experiments per day (8-h work shift), a very low residual acceleration of less than 10^{-6} *g*, and good accessibility to the structures of large-scaled experimental setups in conjunction with favorable experiment costs. This facility represents a global innovation. It is currently under construction at HITec and will be open to the entire scientific community for experiments from 2018 onward.

MATERIALS AND METHODS

The development of the Einstein-Elevator started in 2009 with a proposal for the HITec building under the auspices of a team at LUH and the collaboration of all partners at the Center for Quantum Engineering and Space Time Research (QUEST), a former cluster of excellence. Together, the following unique mechanical concept was initiated. To describe the Einstein-Elevator's technical capabilities, this section first presents the general structure and the functional description. Next, the additional possible trajectories, the design structure, and technical measures to achieve minimum residual accelerations and high repetition rate are shown. Finally, the structure of the experiment carrier and the options for scientists are introduced.

General Structure and Functional Description

To investigate scientific questions using the Einstein-Elevator, an experiment is fitted to the experiment carrier. For the test execution, the test setup is placed in a vertically movable vacuum chamber, called the gondola, which is made of carbon fiber reinforced plastic. Figure 1 illustrates the general structure of the Einstein-Elevator (for further details of the structure, see Lotz et al., 2014). A linear motor is used to accelerate these two components through a brief acceleration phase followed by sudden decoupling along a vertical parabolic trajectory. During the vertical parabolic flight, the gondola travels at a defined distance from the experiment carrier such that the carrier is fully decoupled from its environment and is in free fall. Unlike conventional drop towers, in which the drop path is fully evacuated (Dittus and Schomisch, 1990), the atmosphere in the gondola of the Einstein-Elevator is only a partial vacuum and travels with the experiment—this offers significant time saving when creating the vacuum and hence significantly reduces the preparatory times for experiments.

To guide the gondola and to affix the drive as well as the braking system and the peripherals, a complex steel construction is used. Furthermore, to avoid the transfer of vibrations between the emitting drive and the sensitive gondola, a tower-in-tower design is being implemented. The two independent towers stand on separate ringwall pile foundations. The only connection between the drive and the gondola is a specially mounted coupling rod. The rod transfers the vertical feed forces, while preventing vibrations in the horizontal direction. This design effectively

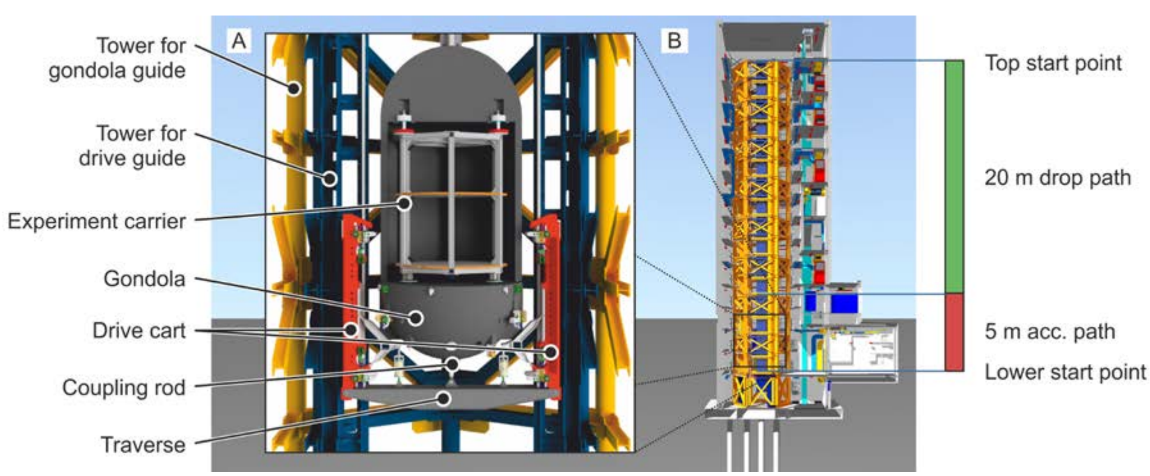

Figure 1. Design of the Einstein-Elevator. (A) Highlighted cut through the steel structure: the gondola with an empty experiment carrier. (B) Sketch of the tower with the division of areas in the tower building.

minimizes the transfer of vibrations into the experiment carrier and also the excitation of the experiment during the acceleration phase.

The initial acceleration and the vertical parabolic flight are controlled by a linear motor along the drop path with a maximum power of 4.8 MW. The linear motor speeds up the gondola together with the integrated experimental setup with an acceleration of 5 *g* from the lower starting position to a speed of 20 m/s within the first 5 m. After decoupling, the drives compensate the air and rolling resistances to maintain the vertical parabolic flight trajectory. The linear motor replaces the catapult function in similar facilities (von Kampen et al., 2006) and offers the additional option of alternative flight trajectories. The drive can be controlled in all areas, such that both the fall section as well as the acceleration section can help simulate different gravitational conditions for specific experiments. In the acceleration section, hypergravity conditions in a range between 1-5 *g* are usable; for example, for the simulation of rocket start conditions. In the drop section, hypogravity conditions between 0-1 *g* are possible; for example, for the simulation of gravity conditions of the Moon or Mars.

The Einstein-Elevator is located in a 39-m-tall building. This overall height is divided into a number of different sections, such as the acceleration section, the section for decoupling the gondola and the experimental setup, and the drop sections. The drop section height h amounts to 20 m. In accordance with Newton's law, this results in a free-fall time $t_{\mu g\_drop}$ of

$$t_{\mu g\_drop} = \sqrt{2h/g} = 2.019\ s \qquad (1)$$

Because acceleration starts from the lower starting point, twice that length of time (4 s) is actually available. In the case of experimental setups that cannot withstand an initial acceleration of 5 *g*, it is possible to trigger a pure free fall from the upper starting position. This results in the calculated free-fall time of 2 s.

The test sequence for a vertical parabolic flight in the Einstein-Elevator is illustrated in Figure 2. The test can been broken into seven sections. At the loading level, or the lower start position, the experiment is loaded into the gondola. Once the vacuum has been formed in the gondola (vacuum <10^{-2} mbar), the experiment is commenced from this position. The gondola is accelerated by the drive over a vertical distance of 5 m to 20 m/s (section I). This is followed by section II, in which the gondola separates from the experiment carrier located on the inside by a distance of 1 m. The controlled trajectory of the gondola and the automated centering mechanism for aligning the experiment carrier after the test execution implies that no gripping mechanism is necessary for the separation process as is generally used in other facilities (Dittus, 2001; Dittus, 2002). The experiment carrier stands on

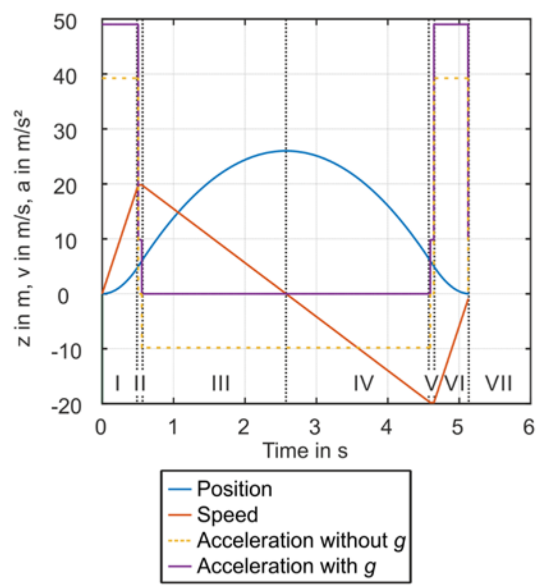

Figure 2. Trajectory profile for microgravity conditions. The coordinate "z" stands for the direction of motion. Description of sections: I. Acceleration section: 5 m; II. Constant travel: 1 m, separation of gondola and experiment; III. Parabolic flight (upwards): 20-m free fall plus 2-m reserve (top); IV. Parabolic flight (downwards): 20-m free fall; V. Constant travel: 1 m, approach and contact between gondola and experiment; VI. Braking: 5 m short-circuited stators, effect of the eddy current brake, plus 2X 4 rows of switched eddy current brake of length 0.5 m each on 2-m onboard brake fins; VII. Contact with hydraulic cylinder.

the floor of the gondola and is not strapped in place, such that the separation process consists exclusively of controlling the gap between the floor of the gondola and the base of the experiment carrier. The experimental setup then separates from the gondola and floats above at a height of 75 mm within the free fly zone of 150 mm during the subsequent free-fall phase. In the separation section and the following free-fall section, both roll and air resistance are compensated by the linear motor. After 4 s of microgravity (sections III and IV), the experiment and the gondola are brought back into contact during section V and then decelerated together in section VI. The necessary braking forces are created in a fail-safe system by a combination of switched eddy current brakes and short-circuited linear motor stators. A hydraulic cylinder (section VII) buffers the residual speed at the end of the test execution, such that the gondola ultimately comes to rest in the original start position.

Additional Trajectories

In addition to the main purpose of experiments under microgravity, other experiments with hypogravity in the range of 0-1 *g* and hypergravity in the range of 1-5 *g* are possible. Unlike previously described microgravity experiments, the gondola and the experiment are not separated from each other during these envisaged accelerations but are permanently attached to one another.

Hypogravity conditions (0-1 g)

To create constant acceleration profiles in the range of 0-1 *g*, two options are available, similar to those for experiments under microgravity. Depending upon the experimental requirement, the test execution can be started either from the lower or upper position. Starting from the lower position, a modified vertical parabolic flight takes place. Starting from the upper position, a braked fall is implemented.

The starting of the test execution from the lower position is similar to that of the microgravity experiments. The experiment carrier is integrated in the gondola and, if necessary, a vacuum is created. The linear motor then accelerates the gondola under profile dependent acceleration (less than 5 *g*) to its resulting and previously calculated initial speed (less than 20 m/s). To conduct an experiment under constant acceleration in the range of 0-1 *g*, the gondola is subjected to constant pushing in the upward direction as well as braking in the downward direction using the linear motor, as shown in Figure 3(A) (light green area). The test duration for the fall distance of 20 m depends upon the programmed profile (between 4 s for the μ*g* profile and 12.7 s for the 0.9 *g* profile). In the braking section, the gondola is decelerated, similar to the microgravity experiments, and then comes to rest at the lower start position. Due to the fixed data connection between the experimental setup and the gondola during these acceleration profiles, the experiment is ready for the next start without any additional alignment or setup.

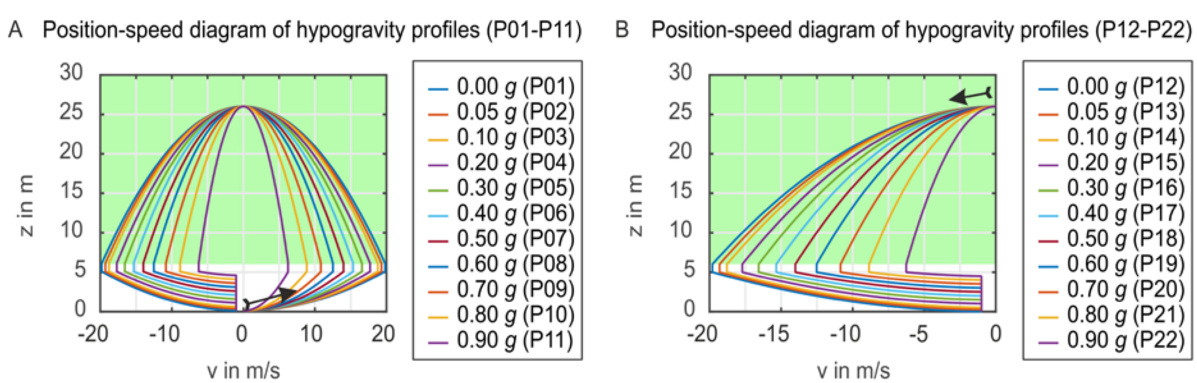

Figure 3. Position-speed diagrams for micro- and hypogravity experiments. The coordinate "z" stands for the direction of motion. (A) Microgravity in parabolic flight (profile P01), hypogravity in parabolic flight (profiles P02-P11). (B) Microgravity in free fall (profile P12), hypogravity in free fall (profiles P12-P22). The key area for the trajectory profiles is the light green area.

To start from the top position, the experiment is introduced into the gondola and, if necessary, a vacuum is created. The gondola is then transported to the upper start position using the integrated crane system. Next, the gondola is disconnected and subjected to constant braking by using the linear motor in accordance with the acceleration profile to match the 0-1 *g* condition, as shown in Figure 3(B) (light green area). The test duration over the 20 m length of the drop section depends upon the accelerations programmed for the experiment. In the braking section, the gondola is decelerated, similar to the conventional microgravity experiments, and then comes to rest in the lower start position. The crane is then used to transfer the gondola back to the upper start position for the next test execution.

The test duration of experiments differing from microgravity conditions depends upon the required and programmed profile. The braked fall travel duration t_{pg_drop} and the modified vertical parabolic flight duration $t_{pg\_sum}=2\cdot t_{pg\_drop}$ are calculated as follows:

$$t_{pg\_drop} = \sqrt{2h/g(1-a_1)} \qquad (2)$$

Considering a trajectory with an acceleration $a_1 = 0.6\ g$, equation (2) indicates a theoretical test duration $t_{pg\_drop} = 3.19$ s in pure drop mode and $t_{pg\_sum} = 2\cdot t_{pg\_drop} = 6.39$ s in modified vertical parabolic flight mode.

Hypergravity conditions (1-5 g)

Experiments conducted under hypergravity conditions take place in the first 5 m of the acceleration section. Further acceleration with *g*-levels > 1 *g* in the free-fall section is not feasible, because the forces to accelerate the gondola are limited in this section to <1 *g*. However, the linear drive's high performance in the acceleration section enables varying hypergravity conditions in the range of 1-5 *g*, as shown in Figure 4 (light green area). The gondola is subjected to constant acceleration in accordance with the gravity conditions required. The speed at the end of the acceleration section is always lower than that reached during weightlessness simulation, such that the gondola simply performs a "normal" vertical parabolic flight at the end of the test without reaching the top position of the tower and is then decelerated in the normal fashion at the end of the test. Besides 0 *g* profile, other hypogravity conditions are also feasible after acceleration phase (light purple area in Figure 4).

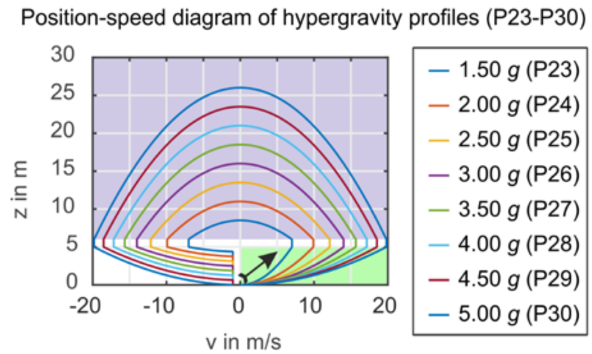

Figure 4. Position-speed diagram for hypergravity experiments. The coordinate "z" stands for the direction of motion. Hypergravity (profiles P23-30). The key area for the trajectory profiles is the light green area. Besides the μ*g*-profile subsequent to hypergravity profiles shown in light purple area, hypogravity profiles are also feasible.

Experiments in the range of 1-5 *g* have an experimental duration t_a depending upon the acceleration profile as programmed. The duration is calculated for the acceleration distance $h_a = 5$ m as follows:

$$t_a = \sqrt{2h_a/g(a_2-1)} \qquad (3)$$

Considering a trajectory with an acceleration $a_2 = 2.5\ g$, the usable acceleration range creates a theoretical test duration of $t_a = 0.82$ s. The simulation of hypogravity conditions in this system is limited to short durations (between 0.5 s for the 5 *g* profile and up to 1.4 s for the 1.5 *g* profile). It is not competitive with that of centrifuges, because these facilities can offer very long durations. However, the new research opportunity in this facility for experiments under hypergravity enables the simulation of processes with very fast acceleration changes. The Einstein-Elevator offers a change of acceleration level from 5 *g* to micro or hypogravity in less than 50 ms. This opportunity can be interesting, for example, for experiments running during simulated rocket stage separation that centrifuges cannot conduct.

Design Structure to Achieve Minimized Residual Accelerations

To attain a minimum residual acceleration during the execution of an experiment, it is necessary to decouple any occurring vibrations from the experiment as much as possible. Due to limited experience in drop tower technologies with guided and driven systems, a mechanical simulation model was built to determine the influence of the structural design with the guides, drive, aerodynamic resistances, and other influences (Lotz and Overmeyer, 2013). Therefore, the experiments and simulations determined the required parameters, such as the aerodynamic resistance of the gondola and the drive carts at test execution, as shown in Figure 5.

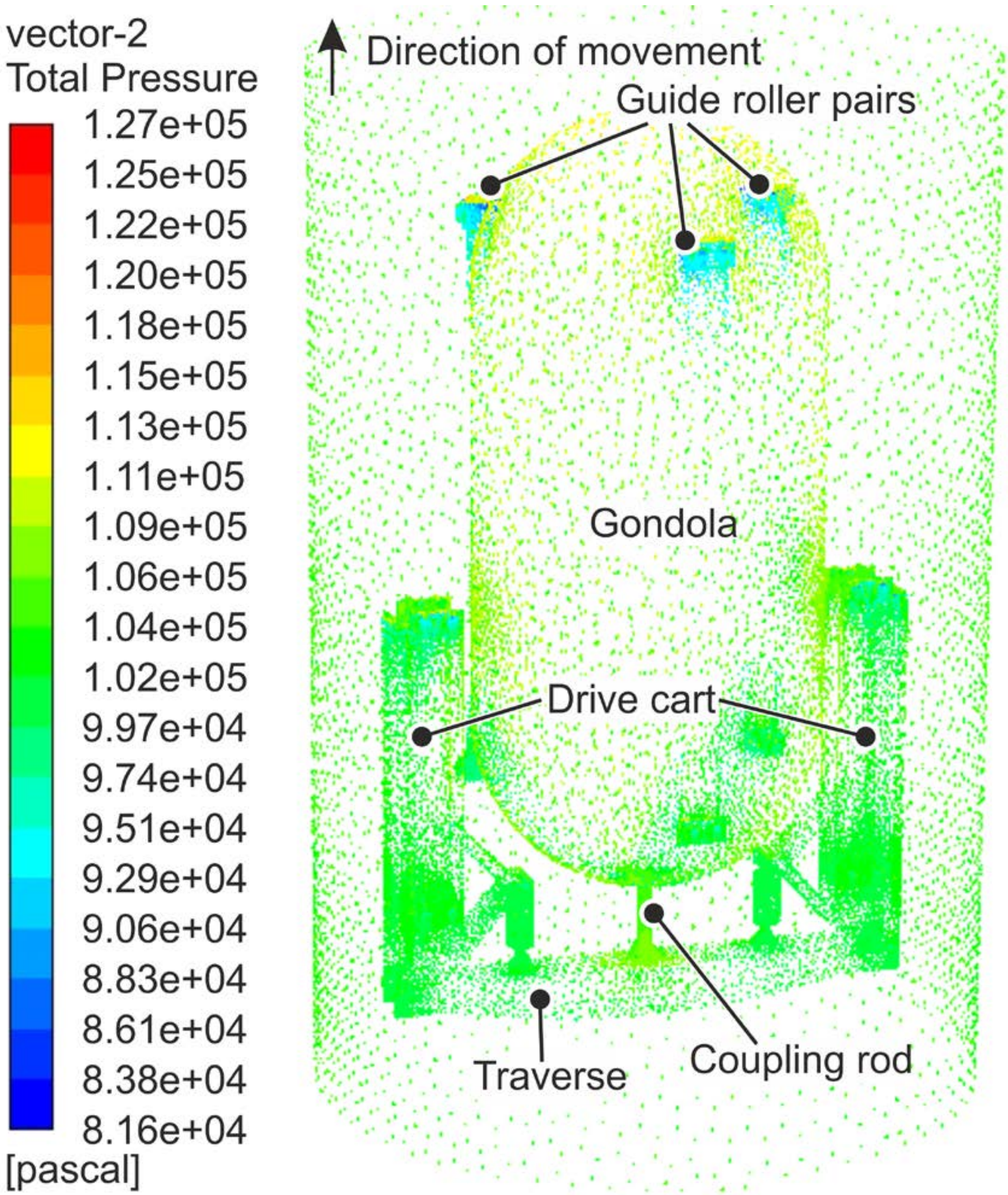

Figure 5. Gondola and drive carts in computational fluid dynamics (CFD) simulation. Results show how the airflow behaves around the moving parts and which pressure and reaction forces occur.

The gondola, the base of which is in contact with the experiment carrier under acceleration, is fitted with low vibration rollers. The rollers, used for guidance purposes, were characterized in prior experiments and tested for their suitability. Figure 6(A) shows the roller test rig developed to analyze the rollers. A characteristic vibration pattern recorded for an individual roller during a simulated test execution in the Einstein-Elevator is shown in Figure 6(B). As a result, the effects on the rollers of the excitation of the experiment carrier may be considered very low (Lotz et al., 2015).

The gondola is only connected to the linear motor via a single coupling rod. Thus any horizontal vibration originating from the drive and its guides can be almost completely decoupled. Vibrations in the vertical direction, originating from the control of the feed forces, are effectively damped by the high inertial mass of the gondola, the traverse, and the drive carts, resulting in relatively low frequencies. The actual design as a deduction of the design sketch is illustrated in Figure 7.

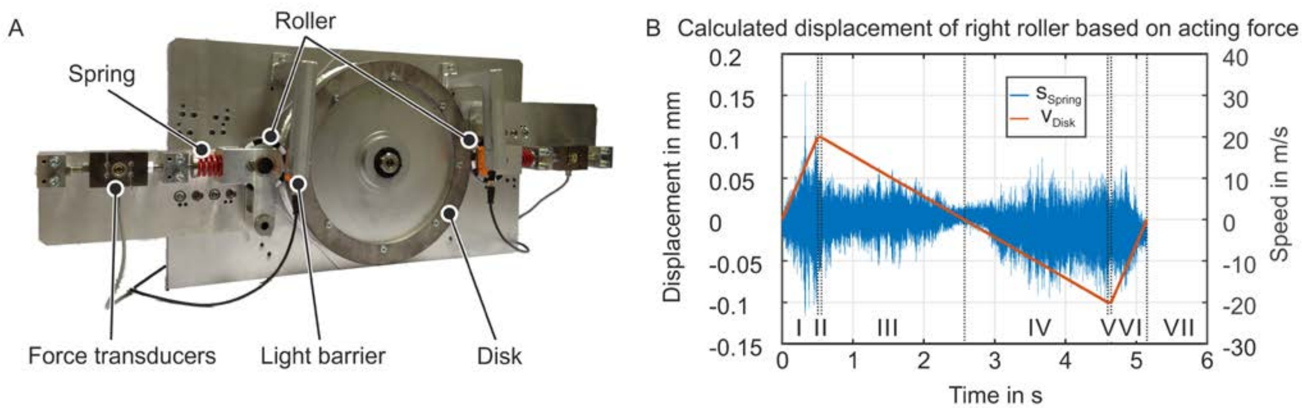

Figure 6. Roller characterizations. (A) Test rig to analyze the behavior of two mounted rollers in combination with the disk surface. The disks represent the guide rails and can be made of different materials to achieve the best combination with the lowest vibration. (B) Vibration amplitudes of one roller and the speed of the driven disk for its movement sections: I. Acceleration; II. Constant travel; III. Parabolic flight (upwards); IV. Parabolic flight (downwards); V. Constant travel; VI. Braking; VII. Waiting for next test execution.

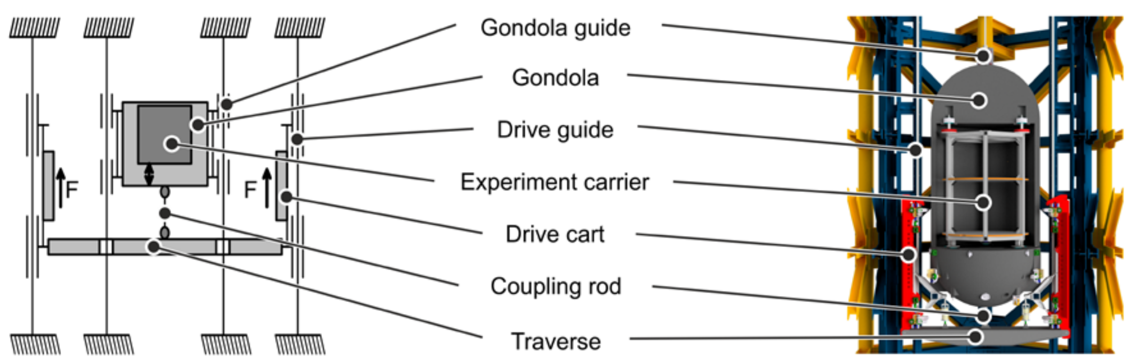

Figure 7. Concept of the Einstein-Elevator. Design sketch to show the general structure of the system and the actual design to display its technical realization.

In addition to decoupling the gondola and drive carts using the coupling rod, the towers that guide the gondola and the drive carts are also separated from each other to create a tower-in-tower design without any points of contact. Both towers are built on separate ring foundations standing on piles rammed about 12 m into the ground. This design is intended to prevent the transfer of vibrations originating in the drive carts through the steel construction into the gondola, which is sensitive to vibrations. In addition to the actual design of the unit, the vacuum atmosphere inside the gondola and an experiment carrier with maximum rigidity and rapid vibration decay will also help in minimizing vibrational influences on the experimental setup.

Technical Measures to Achieve High Repetition Rates

The desire to conduct experiments with minimum effects on quantum level requires high levels of sensitivity and statistics to arrive at validated conclusions. To be able to subtract vibrations from a large number of experiments in a statistical fashion, the aim is to arrange for 100 experiments per 8-h work shift. Therefore, it will be necessary to perform a test every 4 min. This is applicable only under the assumption that the experimental setup does not need to be manually adjusted by opening the gondola, which would cause a long ventilation phase and subsequent vacuum pumping with a loss of approximately 1-2 h, depending on the duration for adjustments and the required vacuum quality. These requirements are only feasible by the innovation of novel drive technologies, a unique gondola concept, and automated test executions.

The Linear Synchron Motor (LSM) drive system (Intrasys GmbH, 2006) is installed along the length of the entire travel path. The stators (active component) are arranged in series along the tower, while the magnetic yokes (passive component) are located on the carts. This design eliminates the need for cable chains to provide power and allows the carts to be designed as passive components, as seen in Figure 8. The drive has two sections. The lower section has six rows in order to generate the high feed forces of approximately 132 kN that are required in the acceleration of the movable parts. In the top area, two rows are used to compensate the air and rolling resistances generated by the gondola and the drive carts. The repetition rate is limited by heating of the drive during the acceleration and braking phases. At the present time, it is assumed that 4 min are necessary and sufficient to allow for cooling. It is currently not intended to install an active cooling system, which would allow for shorter stops for cooling.

To achieve the intended level of precision of the experiments and reflect the maximum permissible residual acceleration during free fall, a vacuum is created within the gondola. To implement high repetition rates, the vacuum is created in the gondola just once prior to conducting the first test execution and is only restored if needed during the 4-min period. This is made possible due to the low leakage rate of the carbon fiber structure and the well-sealed vacuum flanges of the gondola.

To achieve an almost fully automated test execution, as is a prerequisite for the high repetition rates intended, a number of technical solutions have been anticipated, such as automatic centering of the experiment carrier in the closed, evacuated gondola, permanent data access to the experimental data in the control room, and uninterruptible power supplies. After each execution, the experiment carrier can be centered automatically inside the gondola and hence brought into position for the next test, as seen in Figure 9. The realignment of the experiment carrier with the center of the gondola (displacement of approximately 5 mm due to Coriolis force alone) is performed automatically by a lifting function that is controlled externally with mechanical powerless centering and re-lowering into position. Since processes such as necessary vacuum restoration and centering take a certain amount of time, it is not thought to be feasible to greatly increase the repetition rate of experiments above one every 4 min.

Permanent data access enables adjustments to be made within the 4-min parking time to prepare the experimental setup for the next test execution. The experimental data can be downloaded and new parameters can be uploaded. Data access is also enabled during the full experimental execution by way of optical data couplers between the experimental setup and the gondola as well as between the gondola and the base station. The power supply integrated into the experiment

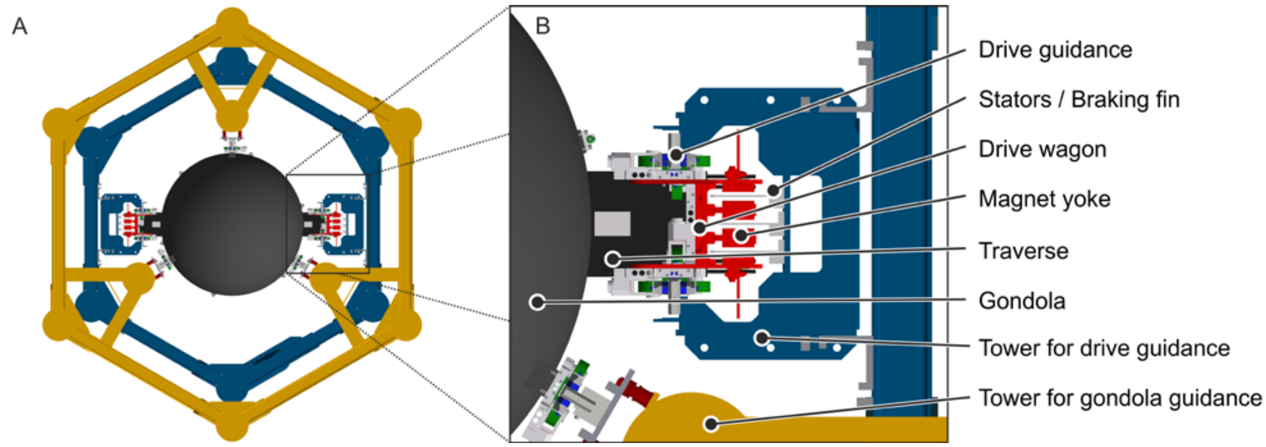

Figure 8. Detailed overview of the drive configuration. (A) Top view of the tower-in-tower construction. (B) Section with the highlighted drive configuration.

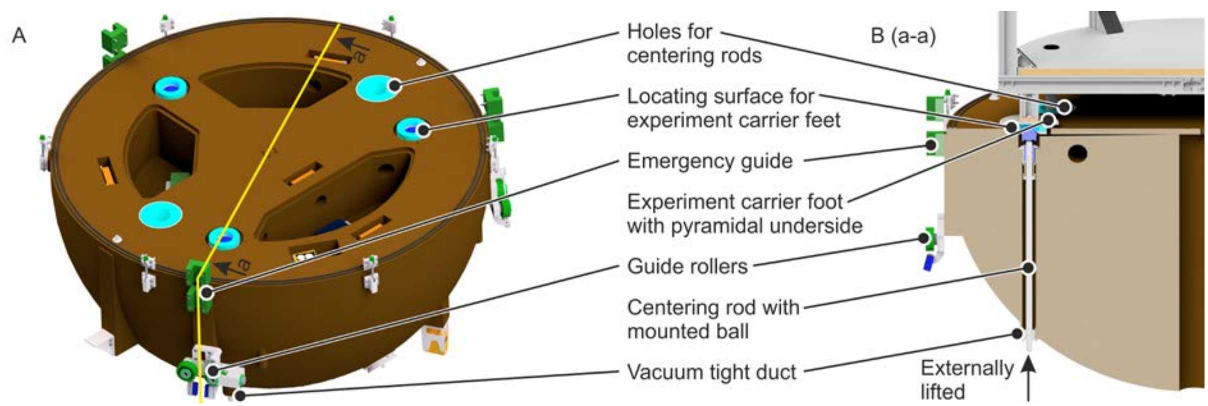

Figure 9. Gondola lower shell and automatic centering unit. (A) Gondola lower shell with its interior and marked cut a. (B) Cut a-a shows the details of the automatic centering unit. The rod with a ball mounted on top is being pushed upwards. Pyramid-shaped counterparts at the three legs provide the self-centering capability of the experiment carrier inside the evacuated gondola.

carrier is charged when in its lower start position and is fully recharged in the 4-min break. The combination of uninterruptible energy supplies and permanent communication means that access to the experiment is available without interruption throughout the test campaign. Further developments are in progress on enabling automatic coupling of additional media. The connectors required for this are planned to be installed near the lower start point.

Structure of Experiment Carrier

The experiment carrier is the platform upon which the scientific experimental setups are affixed. The telemetry, power supply, and communications with the control room are integral components of this platform. A number of other drop towers operate on very similar designs. They are described in the following literature: Neumann, 2006; Könemann, 2009; Selig et al., 2010; Selig and List, 2011; Selig and Liorzou, 2013. These designs generally comprise a carrying frame made of light metal sections with floors arranged between them to allow assembly of the experimental equipment. A pressure-tight shell envelops the experiment carrier in the structure. The shell also serves to allow a normal atmosphere in its interior, since the vacuum atmosphere is actually in the gondola, which represents a source of interference that would hinder proper functioning of the electronics. Figure 10 illustrates the concept for the experiment carrier intended in the Einstein-Elevator.

Figure 10(A) shows the experiment carrier in its closed state. The shell is made of aluminum sheeting. It is pressure-tight and has a slight electromagnetic shielding effect. Two rods are fitted on its base and top to serve as drift and twist stops. The rods of the experiment carrier do not touch the gondola during free flight. If the carrier drifts too far in the direction of the gondola's wall or twists by more than 4°, the rods come into contact with the rings, which are made of a damping material and fixed to the top and the bottom of the gondola, thereby protecting the experimental setup, the experiment carrier, and the gondola. Damping rings are also fitted below the base of the rods to buffer the experiment carrier in case of vertical impacts against the top of the gondola. The two rods not only prevent drift and twisting but also include contacts for the power supply to recharge the battery. The lower side of the experiment carrier includes a transparent window to allow for optical data transmission. Compressed air, gas, and cooling water connections are also attached to the base. In a future phase, it is intended that these are automatically coupled with the gondola when it is in its lower start position.

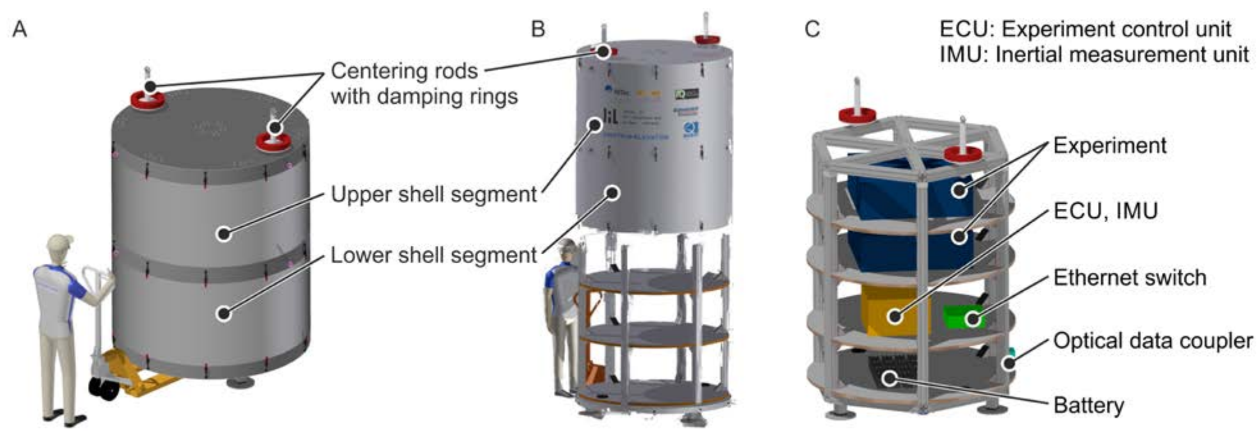

Figure 10. Structure of the experiment carrier. (A) Closed with pressure-tight shell. (B) Opened with lifted shell. (C) Example of the arrangement of the components in the experiment carrier.

Figure 10(B) illustrates the carrier with the shell, which comprises a two-section design. It can be lifted either completely, as illustrated, or separately. The shell and carrier structure are connected with one another using twelve quick-release clamps. This allows for rapid opening with minimal handling. The shell itself is lifted and rests on special attachment points.

The frame of the experiment carrier is illustrated in Figure 10(C). It has a height of 2 m and a diameter of 1.7 m. The experimental setup and the supporting structure may not exceed a combined weight of 1,000 kg. It is made up of standardized aluminum sections. This allows both inexpensive construction as well as simple modification at any time. The floors are made of aluminum sandwich boards with an aluminum honeycomb structure intended to increase rigidity and the moment of inertia and therefore prevent bending during the test execution in the various acceleration phases. The number of floors can be adjusted according to their need. Only the bottom floor is a fixed part of the carrier structure. The floors are designed to carry loads of up to 250 kg. The lowest floor is reserved for telemetry and communication equipment.

The arrangement of the experiment carrier is shown schematically in Figure 10(C). The experiment carrier has an Ethernet connection via optical data couplers and offers a data rate of up to 100 Mbit/s between the control room and the experimental setup, even during test execution. The following interfaces are planned to the experiment: Ethernet and power supply (battery buffered) as well as clock and trigger signals to synchronize the various systems. The experiment carrier will also include a permanently installed computer system with an experiment control unit (ECU) and an inertial measurement unit (IMU). The IMU will collect the telemetry data and transfer them to the control room. The instrumentation includes accelerometers in various precision ranges, gyroscopes, pressure and temperature sensors in the experiment carrier, pressure and temperature sensors in the cooling water circuit, and a charge status display for the battery. Lights and a camera can be deployed when needed. The Ethernet link via the optical data couplers implies an option of permanent access to the experimental setup via the ECU. When the experiment carrier is in its closed shell and when the experiment carrier is outside of the gondola, all connections are also available as standard connections in addition to the automated couplings. For example, the Ethernet would be available and provide a direct link to allow for experimental control outside the gondola.

Options Open to External Scientists

The facility will be open to national and international researchers. Individual access options can be arranged upon request in accordance with the rules of the German Research Foundation (DFG). Scientists will be able to use areas in the building for experiment preparation, the control room for experiment control, and office areas, if needed. The control room and test preparation area are described in the following sections.

Control room equipment

Experiments are controlled via the control room. Four workplaces are intended, as shown in Figure 11(A). Of the four workplaces shown, two will be reserved for facility operating staff with two available for experimental scientists. Live video will be available from the tower, while the equipment system statuses will be shown on monitors or on a large screen projection visible to all operators. The control room will also monitor safety during test execution. This will include, for example, monitoring that all staff have left the tower, access to equipment is locked, all actuators have left the travel zone, and all defined systems are up and running.

The integrated communications system will allow access to the experiments at all times. When the experiment is outside of the tower, communication can take place directly via cable or Wi-Fi with the control room. After inserting the experiment in the gondola, the integrated communication system then takes over. During the test, the experiments are linked via optical data couplers between the gondola and the base station and between the gondola and the experiment carrier, such that control of experiment statuses and the transmission of start and abort commands can be made at any time.

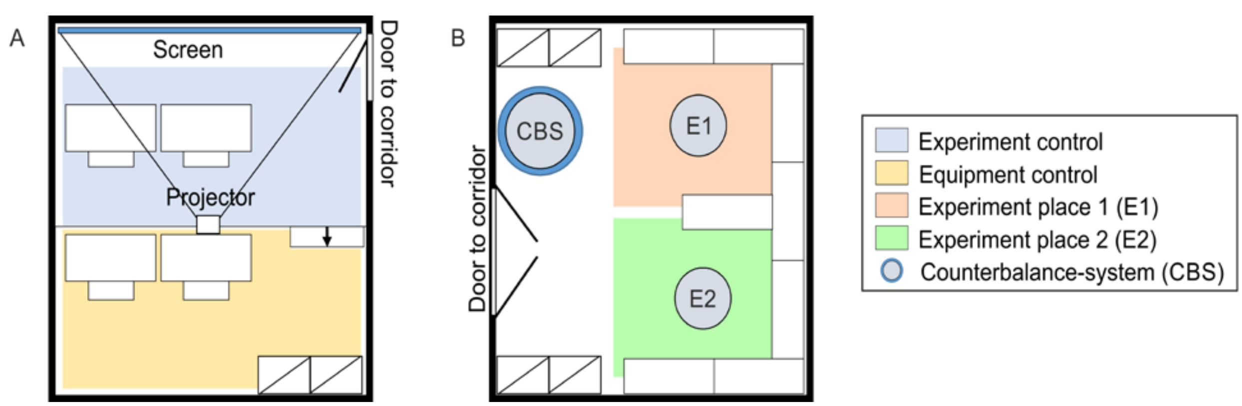

Figure 11. Options for scientists. (A) Depiction of the workplaces in the control room with the areas for facility operating staff and scientists. (B) Test preparation area with two workplaces for scientists to finish the setup assembly (after Lotz et al., 2014).

Experiment preparation area

It is also intended to provide an area for experiment preparation. This room will provide two fully equipped workplaces as well as the necessary counterbalance system (CBS) required prior to test execution. The configuration of the room is shown in Figure 11(B).

The workplaces are equipped with workbenches and are air-conditioned. Each workplace is equipped with compressed air, cooling water, technical gases, and various electrical lines. The prepared experiments are then transported at ground level through the anteroom into the Einstein-Elevator to run the experiment. In addition to the areas available for experiment preparation, research groups will have access to a professional infrastructure comprising temperature-stabilized laser laboratories, clean rooms, workshops, and offices.

Conclusion

The Einstein-Elevator is a unique facility, offering the possibility of 100 experiments per day (8-h work shift) under microgravity. Each experiment will be able to use 4 s in free fall. Furthermore, the simulation of hypo- and hypergravity conditions is possible. The facility can simulate space gravity conditions in the ranges between 0-1 *g* as well as between 1-5 *g*. Experimental setups can have payloads of up to 1,000 kg with diameters of 1.7 m, and heights of 2 m.

HITec offers an excellent research environment for experiments under weightlessness or microgravity as well as hypo- and hypergravity on various topics of different scientific fields. Researchers have access to a professional infrastructure comprising laboratories, clean rooms, workshops, and offices, as shown in Figure 12. The Einstein-Elevator is currently under construction, with first experiments commencing in 2018.

DISCUSSION

Simulation of weightlessness/*microgravity* (approximately 10^{-6} *g*) apart from space is done in sounding rockets, parabolic flights, and traditional drop towers (including drop shafts). Parabolic flights are undertaken regularly as part of complex flight campaigns by the European Space Agency (ESA) and NASA (Del Rosso, 2013; Pletser and Kumei, 2015). These flights allow approximately 20 s in free-fall mode. Sounding rockets can create a free-fall time of approximately 6 min (Preu et al., 2014). Access to these flight-based facilities is time consuming and subjected to restricted safety precautions. For experiments with statistical requirements, rockets and parabolic flights are economically not feasible due to their high cost and low availability.

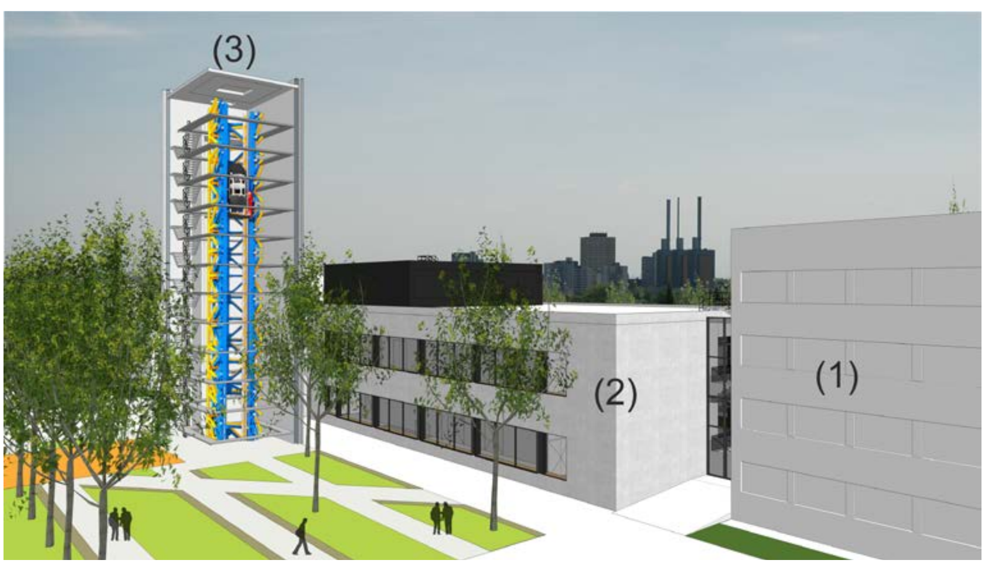

Figure 12. Visualization of the Hannover Institute of Technology (HITec) and the Einstein-Elevator within the Hannover skyline. (1) Offices, (2) Laboratory building, (3) Tower building with the Einstein-Elevator.

On the other hand, conditions such as partial Earth gravity/*hypogravity* for simulating lunar or Martian gravity cannot be performed at a large scale for scientific research in any existing earthbound or flight-based facility. For multiple Earth gravity/*hypergravity* simulation up to 20 *g*, centrifuges are available (van Loon, 2015). However, simulation of fast acceleration changes from multiple Earth gravity to near weightlessness, which occurs for example, during rocket launches, is limited in centrifuges. During a rocket launch, acceleration aborts after cutoff, and the separation of individual stages aborts abruptly. It changes, depending on the rocket type, the stage of the rocket, and the current altitude, from approximately constant acceleration (usually about 5 *g*) suddenly to near weightlessness (Perez, 2012; Hadden, 2015; Lagier, 2016). These changes cannot be simulated in centrifuges. Therefore, a new technique is needed to perform spaceflight, including micro-, hypo-, and hypergravity conditions in a range from less than 10^{-6} *g* up to 5 *g*, with short-time acceleration changes and high repetition rates.

The current possibilities for the simulation of these difficult environmental conditions are trailing behind the development of high precision and specialized sensors, the qualification of production engineering processes for use in space, the development of new production techniques under novel gravitational conditions, and the testing of special equipment for use in space. To achieve the necessary technical advancements for performing applications-oriented research topics, basic physics research is a vital component. Many experiments executed in already established research facilities such as the Bremen drop tower are topics derived from the fields of quantum research, atomic interferometry, and investigations to confirm theories from the fields of relativity theory and quantum physics as well as proving the constancy of natural constants (Ahlers et al., 2016; Kulas et al., 2017). Research is also underway on the propagation of flames as well as the processes in bio-medical engineering and metal alloys (Breuer, 2010). In the future, applications will be feasible for Earth-based processes, which were previously not possible due to gravity.

The complex and high-tech experiments necessary today frequently require straightforward mechanical structures, easy accessibility for development work, and a high repetition rate for statistical evaluations. The goal, therefore, was to develop a cost-effective option in order to quickly test many different specimens with a straightforward test setup. These considerations are reflected in a new facility type that offers a high repetition rate with low minimal residual acceleration and high levels of accessibility for large and heavy experiment carriers with commensurate minimized test costs.

As a result of the disadvantages in terms of accessibility, costs, new focused gravitational conditions, and the extremely limited payloads available in the facilities described above, a number of new research environments are being planned and constructed. The proposed GraviTower Bremen (Könemann et al., 2015) and the scheduled modification of NASA's 5.2 Second Drop Tower (Urban, 2015) together with the Einstein-Elevator represent a new generation of drop towers, which will enable space research to be undertaken much more simply on Earth. The new Einstein-Elevator research facility closes this gap first and makes it possible to conduct fast, simple, and frequent micro-, hypo-, and hypergravity experiments at lower costs.

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