

A Comprehensive Evaluation of Microgravity Platform Technologies

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Abstract

Living on a planet with gravity conditions always means that we should consider the effect of these conditions for research and experiments. This condition, *gravity*, plays an important role in advancing quality of life. For decades, scientists have tried to develop devices capable of simulating various gravitational conditions, with a particular focus on microgravity environments. Microgravity platforms replicate space-like conditions. These platforms, whether located on the ground or in space/sky, offer an opportunity to study and develop various concepts.

Introduction

Due to our existence on Earth, an environment with gravity, scientists have always searched for alternatives to simulate microgravity conditions for their research. Finding an environment with microgravity conditions was nearly impossible on Earth, but it was possible outside our planet. However, experiments conducted in actual physical spaces are costly and challenging to carry out. As a solution, scientists considered simulating space-like conditions in such devices. The history of these simulation devices dates to the late 19th century, with the invention of the clinostat by VanSachs [1,2]. Since then, various methodologies have been used to replicate microgravity conditions for scientific research and technological advancement. These methods cover a wide range of techniques, including advanced technology parabolic flights, drop towers, centrifuges, air-bearing platforms, liquid-based systems; in addition, modern technologies such as magnetic force-based and acoustic levitation methods are also employed. Parabolic flights follow specific flight paths to create intervals of weightlessness [3], while drop towers use controlled free fall in vacuum chambers to eliminate disruptive drag forces [4]. The centrifuge works with the principle of sedimentation due to gravitational force, which spins the particle at high speed [1]. When it comes to Air-bearing platforms, they replicate microgravity environments by using advanced air-bearing systems, while neutral buoyancy facilities achieve weightlessness by carefully balancing buoyancy and gravitational forces in a liquid medium [5]. Magnetic levitation uses magnetic fields to counteract gravitational forces that allow samples to float freely [6]. In contrast, acoustic levitation uses acoustic waves to levitate samples, allowing them to float in mid-air without any physical contact [6].

Thus, this paper provides a review of the previously mentioned microgravity platforms, discussing the working principle of each, along with their advantages and disadvantages. It concludes with a comparison & summary.

Parabolic Flights

Parabolic microgravity flights involve flying an aircraft in parabolic trajectory to minimize gravity and simulate microgravity conditions for short periods of time. As shown in Figure 1, there are three stages of parabolic flights. The first stage is the Pull-Up, where the aircraft ascends at a 45° angle rapidly, causing a high increase in g-forces (hypergravity). Next is the Pushover, and at the peak, the aircraft traces a parabola, creating a brief period of microgravity ($\sim 10^{-2}g$) for 15-20 seconds. These altitudes can range from 7.3 to 10.4 km. Finally, the Pull-Out occurs as the aircraft descends, experiencing hypergravity again before returning to normal. Crew members experience g-forces between 2g and 2.5g during Pull-Up and Pull-Out [7,8].

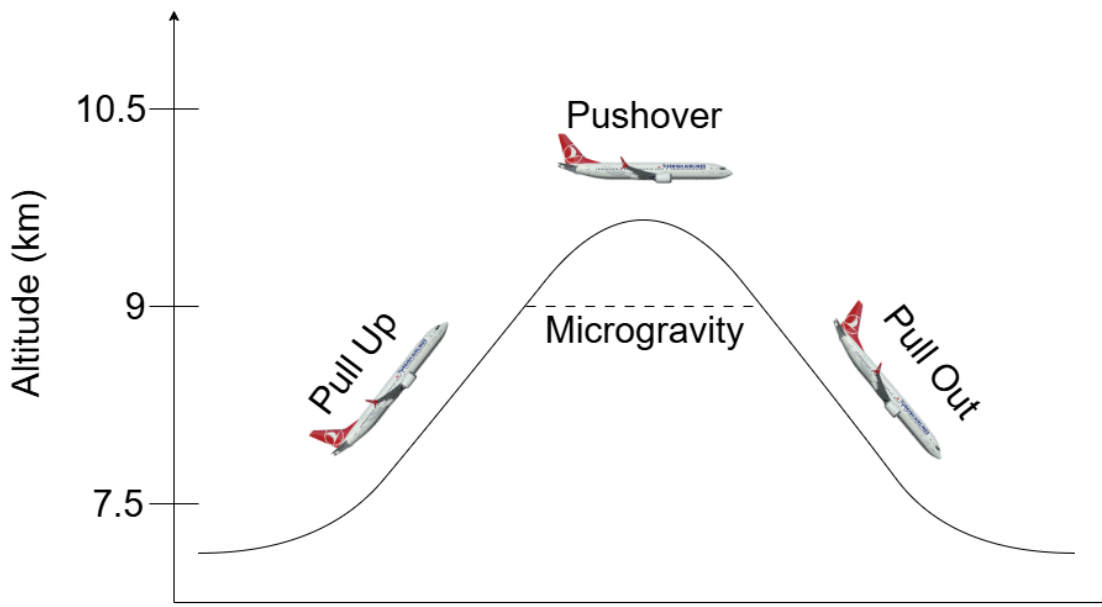


Figure 1. Working principle of parabolic flights.

Fast experiment feedback of parabolic flights offers a significant advantage, as it allows for late access and early retrieval of samples, with experiments typically implemented within months. Another advantage is the flexibility of parabolic flights. Researchers can do multiple experimental runs within a few days, use standard laboratory equipment, and directly make adjustments to the experiments during the flight. By adjusting flight maneuvers, it is possible to simulate gravity conditions found on different planets, such as Moon and Mars, which is a big advantage [9].

However, there are several disadvantages of parabolic flights. The first is the issue of hypergravity. The existence of hypergravity makes the results more complicated, as it interacts with the microgravity phases. Therefore, hypergravity should be taken into account when interpreting the results. Another disadvantage is the limited duration. Microgravity is only achieved for short durations of 15-20 seconds, limiting the amount and the size of the experiments that can be performed. A further disadvantage is the cost. Flying a big plane is relatively costly compared to other

types of microgravity. Operating a large aircraft continuously is surely costly, but a bigger concern would be the energy demand and usage. Conducting many experiments using parabolic flights releases huge amounts of greenhouse gases and uses energy, which could negatively impact the environment.

Parabolic microgravity flights are a useful method for experimenting in microgravity environment easily, allowing the researchers to observe changes during experiments and training astronauts to experience microgravity. However, these flights come with limitations, including short microgravity durations, hypergravity, high costs, substantial energy usage, and environmental impact.

Drop Towers

Drop towers are facilities that allow experiments to experience microgravity by dropping them in an evacuated chamber to eliminate drag and friction forces. They are often used for short-term experiments where a few seconds of microgravity is enough [9]. In a drop tower setup, a payload is placed on a platform at the top of the tower as seen in Figure 1, which is then dropped from a significant height inside a large vacuum tube. The fall creates a near-weightless condition, simulating microgravity. Finally, at the Braking point in Figure 2, the platform slows down. The duration of the microgravity phase usually lasts from a few seconds to nearly ten seconds, which depends on the height of the tower [4].

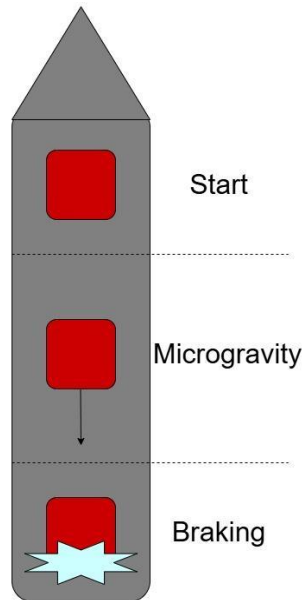


Figure 2. *Functioning of a drop tower*

Drop towers are used in various areas, such as conducting short-term technological investigations, testing materials for space applications, and preparing for long-duration missions. In biology, drop towers have been used to conduct experiments on gravity-axis and membrane physiology. These

include studying the effect of microgravity on the electrophysiology of biological membranes and the orientation behavior of ciliates and fish [9].

Drop towers have many advantages, one of which is the high microgravity quality. Drop towers offer some of the best microgravity levels, as low as 10^{-6} , which is useful for simulating gravity in space. Another advantage would be the short experiment cycles, which enable multiple experiments to be conducted within a few days, and the time between experiment planning, development, and execution can be relatively short. Real-time monitoring and adjustments are other significant advantages of drop towers. Experiment hardware can be changed at short notice, and the setup can be adjusted or improved between drops. Real-time monitoring of experiments is possible, with both data upload and download available during the experiment. Environmental parameters such as temperature and pressure can be regulated during each experimental session, and electrical power is supplied, which is also an advantage. The cost plays a huge role in choosing microgravity platforms and drop towers' medium cost and easy-to-handle safety requirements make them a good choice [9].

Drop towers, of course, have disadvantages, one of which is transient accelerations. Samples undergo transient acceleration, especially during the loading and breaking phases, which can experience up to 50g. Payloads must be designed so that they will be able to withstand these forces. The limited duration of microgravity is a big limitation, with times ranging from 2.2 seconds to 9.5 seconds, making it hard to conduct longer experiments. The size of the payload is another factor to be considered when conducting an experiment in a drop tower, as the size of the drop tower could be smaller than the experiment [10].

Drop towers are valuable for short-term scientific investigations, testing instruments, and preparation of experiments for long missions, despite the challenges of transient accelerations and limited testing time.

Centrifuges

For over a century, scientists have used the slow-rotating clinostat, which was developed by Von Sachs at the end of the nineteenth century [1].

Exploring the impact of a specific parameter is great when we can adjust it in terms of time and magnitude. This is done to explore gravity: by bringing the magnitude to a minimum by going into free fall or increasing its magnitude using centrifuges.

Centrifuges are used to simulate microgravity conditions for various scientific experiments, particularly in space research. The concept revolves around the "Reduced Gravity Paradigm," which suggests that the physiological and biological reactions observed when transitioning from hypergravity to lower gravity levels can be comparable to those experienced in real microgravity environments [1].

In a centrifuge, the sample experiences acceleration due to constant change in direction as it is fixed to the center of rotation. If the sample were to detach, its inertia would make it fly off in a straight line; It would no longer be accelerated and would "lose" its weight. To understand the characteristics of the centrifuge better its formulized as physical relation in

$$a = r \cdot \omega^2 \text{ or } G = r \frac{\omega^2}{g}$$

where:

“a” is the acceleration (inertial) field, “r” is the radius of rotation, “ ω ” is the rotation rate (radians/time), “G” is the field characteristic (the weight-to-mass ratio), and “g” is the Earth's gravitational constant. [38]

Moreover, centrifuges are applied in several fields such as material and particle technology for processes such as separation, nanomaterial classification, casting, and combustion. Also, it's used in geology and life sciences. [1].

Centrifuges provide advantages when used in microgravity research, especially in simulating conditions that are similar to space environments. The first advantage is simulating reduced gravity conditions [1], which we mentioned earlier that this device mimics the space conditions on Earth. Additionally, centrifuges are used in space to create artificial gravity [12]. The second advantage is controlled experimental conditions [1,11], by using centrifuges researchers can control the gravity level for their experiments. For example, a rotating CubeSat can provide access to three kinds of low-gravity conditions: zero rotation (freely floating material), constant rotation (milligravity), and changing rotation (torque changing the g-vector, applying shear) [13].

In addition, these devices are considered an affordable means of accessing microgravity [13]. those devices are cost-effective compared with drop towers or parabolic flights; besides this, centrifuges can provide a more stable environment and longer durations (Drop towers and parabolic flights can attain microgravity and milligravity conditions on Earth for short durations (~1–10 s), but long-duration experiments require an accelerating frame of reference in space (such as a centrifuge or constant-thrusting rocket) or on the surface of a small body [13].

Moreover, they are equipped with different safety devices as shown in Figure 3. to prevent traumatic events and the leakage of potentially infectious fluids, such as biological fluids [14].

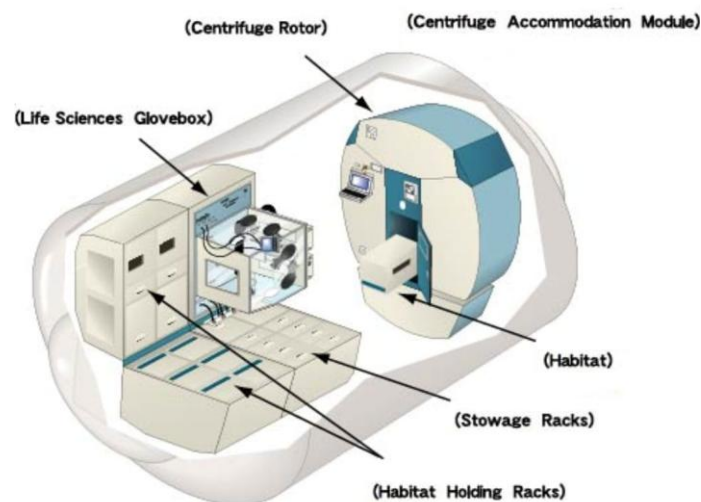


Figure 3. Centrifuge Representation

One of the most important advantages is versatility in experiments [1- 12]. Centrifuges are used in a wide range of applications, including biological samples [9] (for example, one of the centrifuge's main missions is to investigate how gravity affects in hematology, immunology, neuroscience, plant physiology, radiobiology, etc.) [13,15], as well as in fluids and materials sciences.

Each device has its own disadvantages, and so does the centrifuge. In a lab environment, these devices generate noise and heat [17], due to their high-speed operation. Additionally, centrifuges may cause anomalies and biases in samples [13,16] leading to failure in experiments and potentially misleading the researchers about the side effects of the sample.

In conclusion, considering the advantages and disadvantages mentioned earlier, this shows that the centrifuge is a valuable tool in laboratories and space research.

Liquid Based Microgravity Systems (Buoyancy Tanks)

Liquid-based microgravity systems simulate microgravity by balancing the buoyancy force with the gravitational force. When an object achieves neutral buoyancy in a liquid, it doesn't sink or float but remains stable, which is visible in Figure 4. This principle is used in neutral buoyancy facilities, where the object is put in water to simulate weightlessness experienced in space [9].

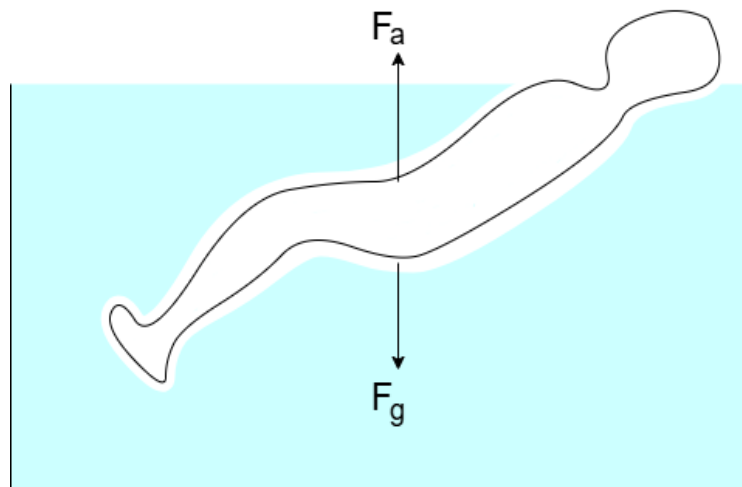


Figure 4. Mechanism of a buoyancy tank.

There are several advantages of liquid-based microgravity systems, such as realistic simulation. Neutral buoyancy provides a realistic simulation of an astronaut experiencing microgravity in space by balancing the forces of gravity (F_g) and water buoyancy (F_a), making it ideal for training and testing. The controlled environment is very useful as the parameters, such as temperature and pressure, can be controlled, providing useful information on variable conditions in space. Liquid based systems are relatively inexpensive and easily reachable when compared to other types of microgravity platforms, considering the only need is a liquid, such as water, and a tank [5].

One of the disadvantages of liquid-based systems is the partial simulation. While neutral buoyancy effectively simulates weightlessness, it does not fully simulate the microgravity environment of space. The need for large water tanks and the requirement to maintain specific conditions can also be difficult, and the pressure of the liquid can also affect the experiment.

Water-based microgravity systems, such as neutral buoyancy, are valuable tools for space training and research. They provide a practical and effective way to simulate weightlessness, allowing astronauts to practice in a controlled environment. Despite the drawbacks mentioned above, the benefits of liquid-based microgravity systems in preparation for space missions are significant, making them a crucial part of space training. Overall, while not being a perfect tool for simulating microgravity, water-based systems play an essential role when researchers try to understand and prepare for the challenges experienced in space [9].

AIR-BEARING SYSTEMS

Air-bearing microgravity platforms are designed to simulate microgravity conditions on Earth, creating a controlled environment for testing and experimenting with space technologies. These platforms use air-bearing systems to replicate space environment where there is almost no gravitational pull [9].

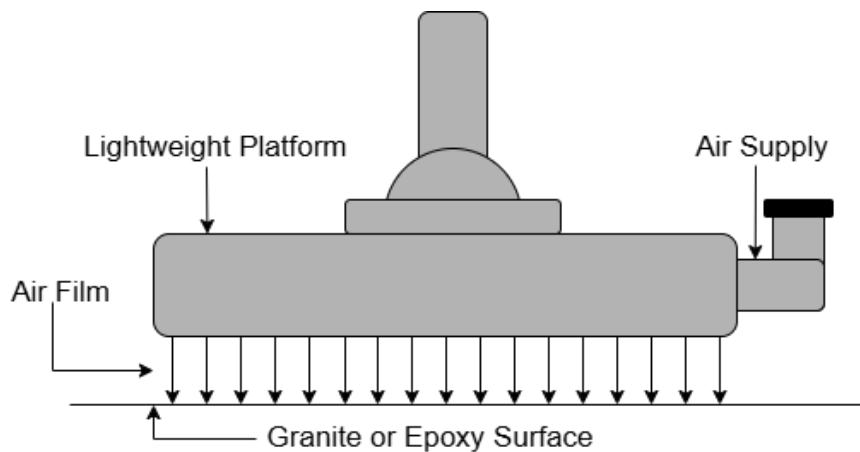


Figure 5. Operational concept of air-bearing systems.

Air-bearing platforms work by using pressurized air to create a thin film of air between the platform and a smooth, flat surface such as granite or epoxy, which can be seen in Figure 5. This setup removes mechanical contact and friction, allowing the platform to float and move freely in a planar environment. The essential components of these platforms are the air bearings, which are placed under the lightweight platform. These bearings blow high-pressure air towards the surface, lifting the platform and enabling it to move smoothly. This levitation simulates almost zero gravity in space, making it possible to test several systems under microgravity conditions to see how they react. Most

air-bearing platforms provide three degrees of freedom (3-DOF), which include movement in the x and y axes and rotation around the z axis. Advanced platforms can offer additional degrees of freedom by using spherical air bearings and some other mechanisms to allow more complex motions [18, 19].

Possible applications for air-bearing platforms would be simulating the movement and connection between two spacecrafts. Physics also uses air-bearing systems to conduct gravity-dependent experiments. Material science and engineering is another branch which uses air-bearing platforms. These platforms can test how different materials react to microgravity [20].

An advantage of air-bearing systems is the low cost compared to the other methods of simulating microgravity. Air-bearing platforms are much more inexpensive and allow longer experiments. Low disturbance by the environment is another advantage of air-bearing systems. The simulated microgravity environment is significantly more stable, with disturbances much less than those experienced in the other, more expensive microgravity platforms discussed earlier. Compared to the other types of microgravity platforms, air-bearing microgravity platforms have relatively lower energy consumption.

One disadvantage is the limited DOF. Traditional planar air-bearing platforms are limited to motion in a single dimension, which can restrict the variety of possible experiments. Fortunately, newer designs are removing this limitation by adding additional degrees of freedom with affordable complexity. Surface imperfections are also a disadvantage, considering the performance of these platforms can be heavily affected by the quality of the flat surface they operate on. Even the smallest unevenness can create disturbances that affect the experiment. Environmental sensitivity is another disadvantage that needs to be taken into consideration. The room the air-bearing platform operates in should be dust-free, have stable temperatures and humidity levels, as well as minimized vibration [9,18,21].

In conclusion, air-bearing microgravity platforms provide a versatile and effective way of simulating space conditions on Earth, contributing to technological development, sensor testing, education and more.

Magnetics

Microgravity based on magnetic forces is one of the methods for creating a quality microgravity medium. The main principle of this method arises from magnetic force caused by the magnetic fields against gravity. In microgravity based on magnetic forces, the system creates a “weightless” condition on the object by counteracting the effects of gravity, rather than using a gravity-free medium. This system uses magnets or electromagnets to generate a magnetic force that counteracts gravity, causing the object to levitate. By using different configurations of the magnets; diamagnetic levitation, magnetic compensator, electromagnetic levitation, electrodynamic levitation applications create a microgravity medium. These applications reach gravity-free conditions or extremely low gravity conditions. There are many sectors and industries using approximately zero-gravity to investigate fluid droplets or small, lightweight (approximately 20 gr) objects [22]. This

system is used in the levitation of magnetic microrobots [25] and in the examination of small organisms such as frogs, fruit flies, and plants [9]. In addition, this system is used in biology to investigate bacteria growth [24] and DNA structures in microgravity environments [9]

Diamagnetic Levitation application which is a technique to create microgravity based on magnetic forces allows levitating micro-particle and droplet in the system [9]. In this application, superconductor and diamagnetic materials are used to achieve levitation. Diamagnetic materials have a property that repels the strong magnetic fields, so that diamagnetic materials influenced by the magnetic fields enable microgravity conditions. As seen in Figure 6, a microgravity environment is created on the suspended magnet using lifting and diamagnetic materials. In the system shown in the figure, a fixed lifting magnet creates a pulling force on the suspended magnet located between two diamagnetic materials. The diamagnetic material creates a pushing force against the magnetic field and provides stabilization of the system in suspension [26]. Diamagnetic Levitation provides position – manipulation without mechanical contact [23]. Negative and positive magnetophoretic applications based diamagnetic levitation are realized to analyze cellular structure (approx. 3 min.) under microgravity conditions, as well as the assembly of the cells and cell-labelling process [23,27]. Electromagnetic Levitation application is another technique, which includes coils and a ferromagnetic object, which is located close to the coils. When high frequency current is passed through the coils, a magnetic field is created, and eddy currents is induced in the ferromagnetic object. The interaction of the magnetic field derived from eddy currents and the magnetic field of the electromagnets generates an attractive upward magnetic force on the ferromagnetic object. This magnetic force creates a microgravity medium for the ferromagnetic object [22,30]. Electromagnetic levitation, one of the oldest levitation techniques, is used in material science research. [31].

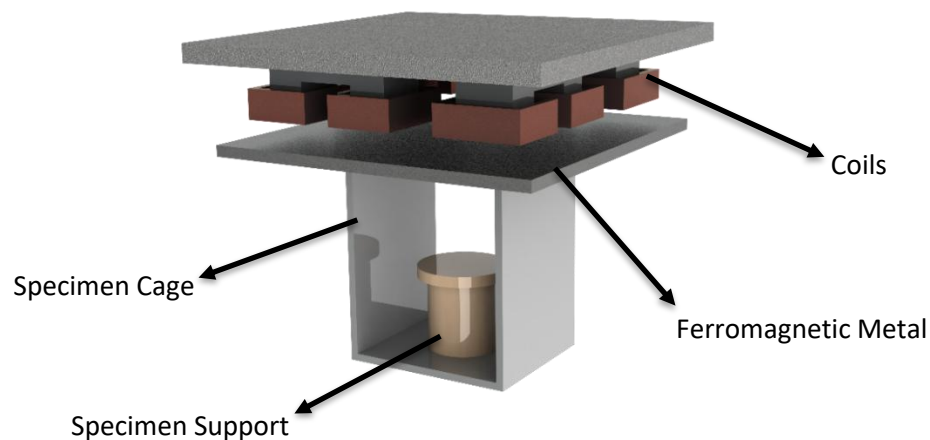


Figure 6. Representation of Electromagnetic levitation

Another technique to obtain microgravity is ‘magnetic levitation gravity compensation system’. This system includes permanent magnet arrays so that it enables compensation of gravity to create microgravity. The system comprises three permanent magnet arrays, which are fixed to the upper and lower stator, and the non-stationary mover section. The magnets in each permanent magnet array are located side by side in opposite vertical directions, as seen in Figure 6. Each permanent

magnet in the mover section is attracted by the upper stator and repelled by the lower stator. Therefore, this system provides the mover section with suspension in the air, generating microgravity medium by compensation of gravity [19]. This technique is a very unstable system and requires a good control system.

In the electrodynamic levitation technique, microgravity is created by the use of variable magnetic fields. This technique includes permanent magnets or electromagnets and a non-ferromagnetic metal object. The translational or rotational movement of the magnets causes variable magnetic flux on the non-ferromagnetic object. The variable magnetic flux generates eddy currents on the non-ferromagnetic object. As the eddy currents create opposite magnetic field direction to magnetic field of the magnets, repulsive forces are observed between the magnets and the ferromagnetic object. Therefore, the microgravity medium occurs through these repulsive forces [28].

Microgravity based on magnetic forces has lots of advantages. Controlling the magnetic forces is an important advantage to adjust the intended gravity medium for microgravity conditions. Moreover, the ability to suspend cells and tissues in the air provides safer and less risky investigations. Microgravity based on magnetic forces allows the examination of applications requiring high precision. Compared to other microgravity systems, the ability to create microgravity based on magnetic forces instantly maintains a quicker and more efficient examination. Contrary to the advantages, there are also disadvantages. In microgravity based on magnetic forces applications, the negative effect of the strong magnetic field on the specimen is a major disadvantage, especially in biological studies. To prevent this problem, paramagnetic solutions are used in the analysis environment [23]. The sample object used in these systems must consist of a metal structure that can interact with the magnetic field. Unlike other microgravity systems, it does not have the ability to suspend all types of objects in the air. This reduces the applicability of the system to all types of materials. Magnetic levitation can only occur in areas where magnetic fields can be created. This restricts the environments to be examined, and energy is consumed to create a strong magnetic field [9]. Additionally, such electromagnetic systems do not have a stable structure and require an active control system [29]

Acoustic levitation

Acoustic Levitation technique is another approach to create a microgravity environment to suspend solid and fluid form objects in the air or fluid environment. [32,33] Acoustic Levitation is an instance of container-less technology which causes levitation by using forces created by the fields that appear under certain conditions. In this technique, standing waves occur, and the result of the standing waves enables light and small objects (100 μ m to 5 mm) [34,35] or fluid droplets to remain in the air or solution without touch. Acoustic Levitation applications are used in many sectors and disciplines to investigate specimens. This method provides a great advantage, especially for disciplines such as biology, chemistry, analytical chemistry, pharmacy and fluid mechanics, in examining liquid drops without contact with any surface.[36,32] Moreover, the acoustic levitation technique enables the view of the fluid droplet in a container-less medium, investigation of the specimens' internal flow, equilibrium form oscillation, and the dynamics in digital microfluid platforms, and synthesis of high purity substances[34]. In contrast with magnetic levitation, the acoustic levitation technique does not restrict the material of the object that will be examined in the microgravity environment. All kinds of materials are used to keep it suspended in the microgravity environment based on acoustic levitation [37].

The Non-Resonant Acoustic Levitation system has opposing piezoelectric transducer and reflector regions. While the transducer region spreads acoustic waves, the reflector region reflects the reflecting waves through an angled direction. As a result of the interaction (combination) of the transmitted and reflected acoustic waves, standing waves are formed between the reflector and transducer. In this region, the acoustic radiation forces raised from the standing waves are calculated by Gorkov's Theory [36]. As seen in Figure 7, Gorkov potential and acoustic pressure regions are created. The acoustic pressure regions push the object to be levitated to areas where the Gorkov potential is low, and as a result, microgravity is created on the object. Changes in the position of the levitated object can cause jumps between areas with low Gorkov potential [32].

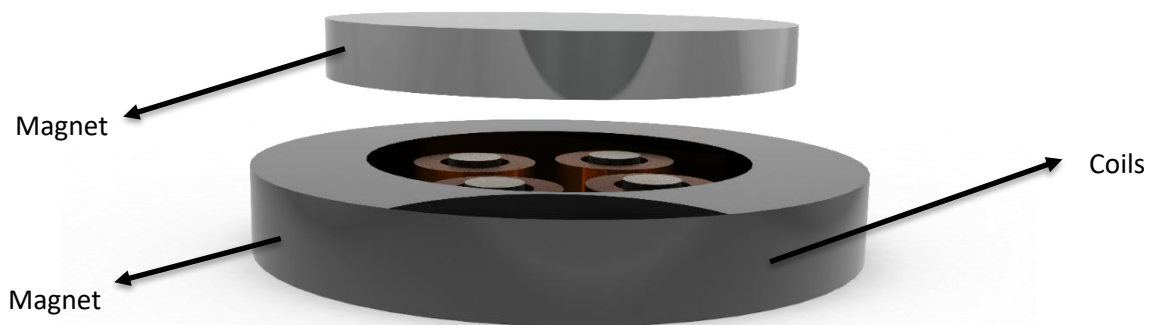


Figure 7. *Electrodynamics levitation system*

Acoustic Levitation with a resonant tube is another technique to create a microgravity medium. This technique has resonant tube, emitter, and reflector regions. Under the condition that the distance between the emitter and the reflector is an integer multiple of the half-wavelength, the reflected backward and forward acoustic waves overlap each other and thus form a standing wave. Acoustic radiation pressure created by standing waves and intense acoustic fields cause levitating forces that suspend the object in the air. The magnitude of the levitating forces varies depending on the created standing waves, acoustic radiation pressure created by acoustic waves, concavity curves of the emitter and reflector, and resonance tube dimensions. The resonant tube prevents external disturbances, such as dust, and it narrows the horizontally spread standing wave. Thus, the resonant tube increases the magnitude of the levitation force in the vertical direction [37].

It is a relatively cheaper method compared to other alternative microgravity applications and is more suitable for continuous work. The compact structure of the acoustic microgravity system provides ease of use. The most important advantage of acoustic levitation in these systems is the levitation of liquid and solid objects and their examination in microgravity without any material restrictions. The weights and dimensions of the objects to be examined in the microgravity environment are very important in the acoustic levitation system. Acoustic levitation provides the opportunity to examine relatively light objects. Although the weight value range of the objects to be

examined changes according to the standing wave fields created, this reduces the levitation capacity of the application. However, environmental conditions such as external dust and dirt negatively affect standing waves. Additionally, one of the disadvantages of acoustic levitation is the inability to maintain a stable structure in the created system.

Comparison & Conclusions

In this paper, we reviewed different microgravity platforms and their advantages and disadvantages.

To compare these platforms, there are several factors to consider. These factors are time duration, cost, volume, payload size (weight), interaction, accessibility, repetition rate and power demand.

For the interaction factor, we can classify these platforms into two categories: Telecommand (TC) and human interaction. The buoyancy tanks and parabolic flights require human interaction. When it comes to the duration of microgravity, drop towers and parabolic flights can attain microgravity and milligravity conditions on Earth for short durations (~1–10 s) [7,40]. In contrast, centrifuges, air-based systems, buoyancy tanks, magnetic levitation and acoustic levitation provide more stability and longer durations, from minutes to hours. Moreover, these are more suitable for continuous work, while drop towers and parabolic flights are better for short-duration experiments.

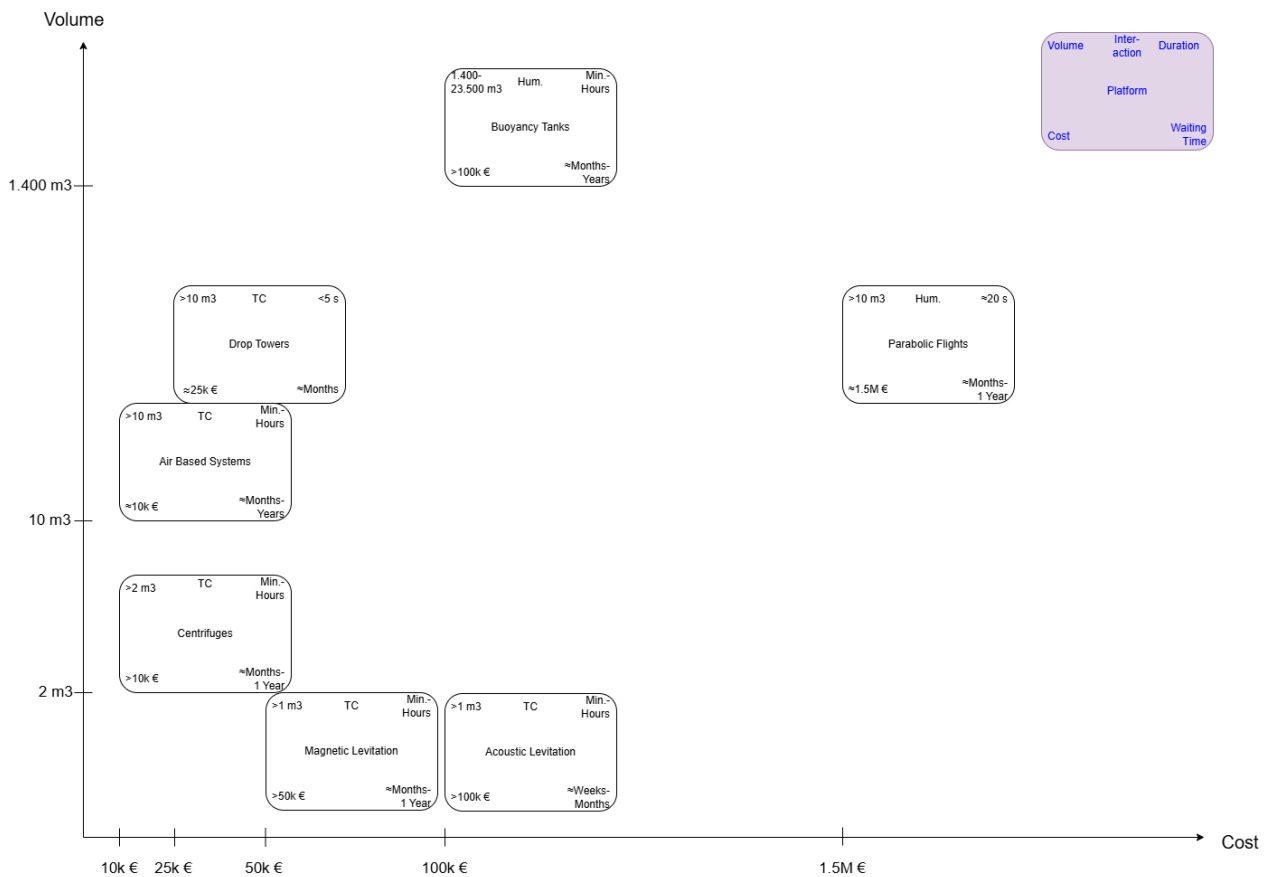


Figure 8. Comparison of microgravity platforms table

In conclusion, microgravity platforms have the same aim, but each platform has a different function to represent these microgravity conditions. These platforms are essential tools for research and also offer a range of advantages & disadvantages to consider when conducting research or experiments. Choice of proper platform is an application specific issue, by taking account of all the pros and cons, one should decide the proper one.

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Resources :

[1] Van Loon, J. J. W. A. (1, 2. Affiliation). "Centrifuges for Microgravity Simulation: The Reduced Gravity Paradigm."

[2] Aditya Vashi, Kamalalayam Rajan Sreejith, and Nam-Trung Nguyen. Lab-on-a-Chip Technologies for Microgravity Simulation and Space Applications.

[3] European Space Agency (ESA). (n.d.). *Parabolic flights*.
<http://wsn.spaceflight.esa.int/docs/EUG2LGPr3/EUG2LGPr3-5-ParabolicFlights.pdf>

[4] European Space Agency (ESA). (n.d.). *Drop tower*.
<http://wsn.spaceflight.esa.int/docs/EUG2LGPr3/EUG2LGPr3-4-DropTower.pdf>

[5] Sun, C., Chen, S., Yuan, J., & Zhu, Z. (2017). A Six-DOF Buoyancy Tank Microgravity Test Bed with Active Drag Compensation. *Microgravity Science and Technology*, 29(5), 391–402.

[6] Szekely, J., Schwartz, E., & Hyers, R. (1995). Electromagnetic Levitation: A Useful Tool in Microgravity Research. *NASA Technical Reports Server*.

[7] Pletser, V., Frischauf, N., Laufer, R., Cohen, D. "Parabolic Flights with Gliders as an Innovative Low-Cost Platform for Microgravity and Hypergravity Research."

[8] European Space Agency (ESA).

[9] Ferranti, F.; Del Bianco, M.; Pacelli, C. Advantages and Limitations of Current Microgravity Platforms for Space Biology Research. *Appl. Sci.* 2021,11,68.

[10] Ruyters, G., Friedrich, U. (2006). "From the Bremen Drop Tower to the International Space Station ISS – Ways to Weightlessness in the German Space Life Sciences Program." *Journal of Gravitational Physiology*. First published: 07 December 2006.

[11] Brinckmann, E. "Centrifuges and Their Application for Biological Experiments in Space."

[12] MIT News. (2015, July 2). *Exercise and artificial gravity in space*. Massachusetts Institute of Technology. <https://news.mit.edu/2015/exercise-artificial-gravity-space-0702>

[13] Asphaug, E., Thangavelautham, J., Klesh, A., Chandra, A., Nallapu, R., Raura, L., Herreras-Martinez, M., & Schwartz, S. "A Cubesat Centrifuge for Long Duration Milligravity Research."

[14] Terry, S.C., Jerman, J.H., Angell, J.B. "Lab-on-a-Chip Technologies for Microgravity Simulation and Space Research."

[15] Japan Aerospace Exploration Agency (JAXA). (n.d.). *Japanese contribution to the ISS program*.
https://iss.jaxa.jp/iss/contribution/issjdoc3_2_e.html

[16] Herranz, R., Anken, R., Boonstra, J., Braun, M., Christianen, P. C. M., de Geest, M., Hauslage, J., Hilbig, R., Hill, R. J. A., Lebert, M., Medina, F. J., Vagt, N., Ullrich, O., van Loon, J. J. W. A., & Hemmersbach, R. "Ground-Based Facilities for Simulation of Microgravity: Organism-Specific

Recommendations for Their Use, and Recommended Terminology." <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9864955/>

[17] Kalstein USA. (2023, March 2). *What are the advantages and disadvantages of using laboratory centrifuges?* Retrieved from <https://kalstein.us/blog/2023/03/02/what-are-the-advantages-and-disadvantages-of-using-laboratory-centrifuges/>

[18] Nakka, Y. K., Foust, R. C., Lupu, E. S., Elliott, D. B., Crowell, I. S., Chung, S.-J., Hadaegh, F. Y. "A Six Degree-of-Freedom Spacecraft Dynamics Simulator for Formation Control Research." [H1-A SIX DEGREE-OF-FREEDOM SPACECRAFT DYNAMICS](#)

[19] Yalçın, B. C., Martinez, C., Coloma, S., Skrzypczyk, E., & Olivares-Mendez, M. A. (Members, IEEE). "Lightweight Floating Platform for Ground-Based Emulation of On-Orbit Scenarios."

[Lightweight Floating Platform for Ground-Based Emulation of On-Orbit Scenarios](#)

[20] Rybus, T., Seweryn, K. (2015). "Planar Air-Bearing Microgravity Simulators: Review of Applications, Existing Solutions, and Design Parameters." *Acta Astronautica*, 120, 239-259.

[21] Zappulla, R., Virgili-Llop, J., Zagaris, C., Park, H., Sharp, A., & Romano, M. "Floating Spacecraft Simulator Test Bed for the Experimental Testing of Autonomous Guidance, Navigation, and Control of Spacecraft Proximity Maneuvers and Operations." *Naval Postgraduate School, Monterey, CA, USA. Floating Spacecraft Simulator Test Bed for the Experimental Testing of Autonomous Guidance, Navigation, & Control of Spacecraft Proximity Maneuvers and Operations*

[22] Nayak, A. (2015). "Controller Design for Magnetic Levitation System" (Master's thesis). *National Institute of Technology, Rourkela, India.*

[23] "Levitation of Cells from Bone Marrow Origin" (Doctoral dissertation). *İzmir Institute of Technology, İzmir, Turkey.*

[24] Dijkstra, C. E., Larkin, O. J., Anthony, P., Davey, M. R., Eaves, L., Rees, C. E. D., & Hill, R. J. A. (2011). "Diamagnetic Levitation Enhances Growth of Liquid Bacterial Cultures by Increasing Oxygen Availability." *Journal of the Royal Society Interface*, 8(56), 334-344.

[25] Hsu, A., Pelrine, R., de Gouvea Pinto, R., & Schaler, E. W. (2022). "2D-Compliant, Diamagnetic Levitating Micro-Robots for Operation on Non-Flat, Non-Clean Tracks." *IEEE Robotics and Automation Letters*, 7(2), 3571-3578.

[26] Simon, M. D., Heflinger, L. O., & Geim, A. K. "Diamagnetically Stabilized Magnet Levitation." *Department of Physics and Astronomy, University of California, Los Angeles; Torrance, CA; Department of Physics and Astronomy, University of Manchester, UK.*

[27] Anil-Inevi, M., Yaman, S., Arslan Yildiz, A., Mese, G., Yalcin-Ozuysal, O., Tekin, H. C., & Ozcivici, E. (2018). "Biofabrication of in situ self-assembled 3D cell cultures in a weightlessness environment generated using magnetic levitation." *Scientific Reports*, 8(1), 1-16.

[28] Sadiku, M. N. O. (2006). "Magnetic Levitation." *IEEE Potentials*, 25(2), 6-11.

- [29] Han, W., & Pengshuai, H. (n.d.). "The Design and Simulation for the Meter-Level Gap Electromagnet Permanent Magnet Fixed-Point Levitation Control System." *School of Mechanic and Electronic Engineering, Xidian University, Xi'an, China*.
- [30] Williams, L. (2005). *Electromagnetic Levitation* (Thesis). [Electromagnetic Levitation Thesis \(uct.ac.za\)](http://uct.ac.za)
- [31] *EML - An Electromagnetic Levitator for the International Space Station*.
- [32] Zhao, S., & Wallaschek, J. (2011). "A Standing Wave Acoustic Levitation System for Large Planar Objects." *Archive of Applied Mechanics*.
- [33] Perez, N., Andrade, M. A. B., Canetti, R., & Adamowski, J. C. (2014). "Experimental Determination of the Dynamics of an Acoustically Levitated Sphere." *Journal of Applied Physics*, 116(18), 184903.
- [34] Sci-Hub. "Compact Acoustic Levitation Device for Studies in Fluid Dynamics and Material Science in the Laboratory and Microgravity." *Review of Scientific Instruments*, 56(11), 2059–2065. <https://doi.org/10.1063/1.113841>
- [35] Li, L., Gu, N., Dong, H., Li, B., & G., K. T. V. (2020). "Analysis of the Effects of Acoustic Levitation to Simulate the Microgravity Environment on the Development of Early Zebrafish Embryos." *RSC Advances*, 10, 44593.
- [36] Andrade, M. A. B., Pérez, N., & Adamowski, J. C. (2015). "Analysis of a Non-Resonant Ultrasonic Levitation Device." *Physics Procedia*, 70, 68-71.
- [37] Jiang, H., Liu, J., Lv, Q., Gu, S., Jiao, X., Li, M., & Zhang, S. (2016). "Analysis and Experimental Study on the Effect of a Resonant Tube on the Performance of Acoustic Levitation Devices." *AIP Advances*, 6(9), 095302.
- [38] Smith, A. H., Fuller, C. A., Johnson, C. C., & Winget, C. M. "Space Station Centrifuge: A Requirement for Life Science Research."