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MicroGravity Explorer Kit (MGX): An Open-Source Platform for Accessible Space Science Experiments

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Abstract: The study of microgravity, a condition in which an object experiences near-zero weight, is a critical area of research with far-reaching implications for various scientific disciplines. Microgravity allows scientists to investigate fundamental physical phenomena influenced by Earth's gravitational forces, opening up new possibilities in fields such as materials science, fluid dynamics, and biology. However, the complexity and cost of developing and conducting microgravity missions have historically limited the field to well-funded space agencies, universities with dedicated government funding, and large research institutions, creating a significant barrier to entry. This paper presents the MicroGravity Explorer Kit's (MGX) design, a multifunctional platform for conducting microgravity experiments aboard suborbital rocket flights. The MGX aims to democratize access to microgravity research, making it accessible to high school students, undergraduates, and researchers. To ensure that the tool is versatile across different scenarios, the authors conducted a comprehensive literature review on microgravity experiments, and specific requirements for the MGX were established. The MGX is designed as an open-source platform that supports various experiments, reducing costs and accelerating development. The multipurpose experiment consists of a Jetson Nano computer with multiple sensors, such as inertial sensors, temperature and pressure, and two cameras with up to 4k resolution. The project also presents examples of codes for data acquisition and compression and the ability to process images and run machine learning algorithms to interpret results. The MGX seeks to promote greater participation and innovation in space sciences by simplifying the process and reducing barriers to entry. The design of a platform that can democratize access to space and research related to space sciences has the potential to lead to groundbreaking discoveries and advancements in materials science, fluid dynamics, and biology, with significant practical applications such as more efficient propulsion systems and novel materials with unique properties.

Keywords: STEM education in space science; space sciences innovation; machine learning in space; microgravity experiments; suborbital rocket flights; Jetson Nano; low-cost instrumentation

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Citation: Moura, W.d.M.; dos Santos, C.R.; Freitas, M.J.d.S.; Pinto, A.C.; Simões, L.P.; Moraes, A. MicroGravity Explorer Kit (MGX): An Open-Source Platform for Accessible Space Science Experiments. *Aerospace* **2024**, *11*, 790. https://doi.org/10.3390/aerospace11100790

Academic Editors: Paolo Tortora and Raffaele Savino

Received: 6 July 2024
Revised: 23 August 2024
Accepted: 20 September 2024
Published: 25 September 2024

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1. Introduction

Microgravity is an important area of research with far-reaching implications for various scientific disciplines. Microgravity, which occurs when the D'Alembert forces nearly balance the planet's gravitational acceleration, allows scientists to investigate fundamental physical phenomena influenced by Earth's gravitational forces [1]. This research opens new possibilities in fields such as materials science by creating stronger, lighter alloys; fluid dynamics through understanding fluid behavior in combustion processes; and biology by observing cell growth and development in a weightless environment [2].

Saenz-Otero and Miller [3] highlights the significant challenge posed by the complexity and cost of developing and conducting microgravity missions. This has historically limited

the field to well-funded space agencies, universities with dedicated government funding, and large research institutions. The substantial resources and expertise required for creating and executing these experiments form a significant barrier to entry. For example, in 2010, a group of middle school students in Brazil developed an experiment to fly aboard the Brazilian VSB-30 sounding rocket, capable of providing six minutes of microgravity. The experiment was simple, measuring the acceleration and deceleration during the flight using a spring-mass system (left panel of Figure 1). They focused on measuring and recording the spring-mass system's displacement rather than on the hardware and software system required to record the images. However, they had to get involved with the tasks related to hardware and software development, making their efforts much more difficult.

Another example comes from the Brazilian institution INPE (Instituto Nacional de Pesquisas Espaciais), which developed an experiment to investigate the influence of gravity on the solidification of a Pb-Sn eutectic alloy. The middle panel of Figure 1, adapted from An et al. [4], shows the experiment. More details about this subject can be found in An et al. [4] and Toledo et al. [5,6]. According to An et al. [4], this experiment studied Pb-Sn and Pb-Te eutectic alloys. The oven was turned on 30 minutes before lift-off, allowing it to reach 500 °C to liquefy the alloys. At the beginning of microgravity, the samples containing the liquid alloys were moved to the cold part of the oven to start the solidification process. Examples of samples adapted from Toledo et al. [5] are shown in the right panel of Figure 1. In such experiments, the samples must be recovered after the flight to be analyzed in the laboratory. These cases exemplify the complexity involved in conducting microgravity experiments on board rockets.

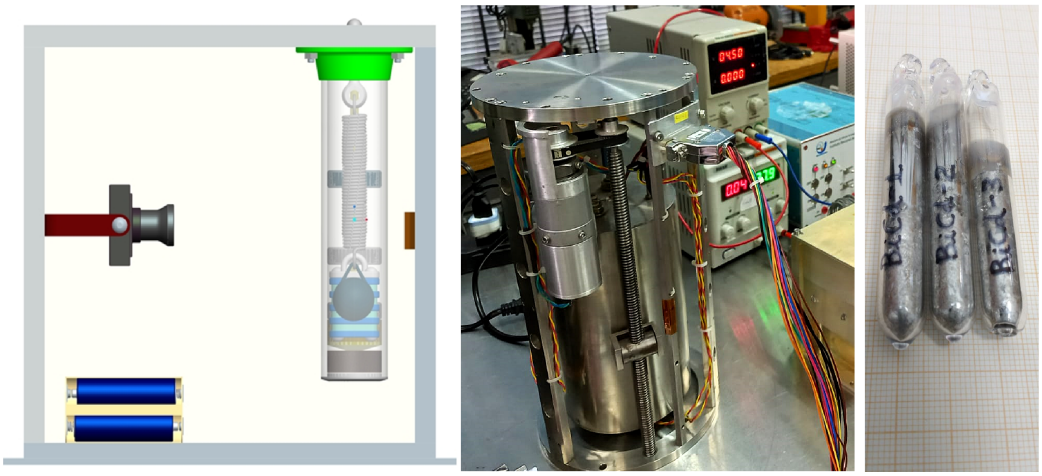


Figure 1. Examples of microgravity experiments. Left panel: Illustration of the spring-mass system educational experiment. Middle panel: Furnace for investigating the influence of gravity on the solidification of a Pb-Sn eutectic alloy. Right panel: Sample ampoules before solidification in the microgravity flight

However, it is important to acknowledge some exciting initiatives in the last two decades attempting to broaden access. The European Space Agency's (ESA) educational experiments, as reported by Pletser et al. [7], involve teachers in parabolic flights, offering a valuable learning experience about the microgravity environment. Similarly, the REXUS/BEXUS program, a sounding rocket and balloon initiative from the German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt), documented by Stamminger [8], provided opportunities for university students to develop and fly their microgravity experiments. These initiatives demonstrate the potential for fostering broader participation in this fundamental research area.

Microgravity is an essential gateway to the space sector, increasing accessibility through specialized programs. These programs enable training new professionals and the development of technologies for future use in rockets and satellites. According to

Perondi [9], the satellite sector is now at a stage of maturity where direct product use and the advent of product-enabled services define this new economic sector. Pessoa Filho [10] notes that this market generates over $300 billion annually, driven mainly by satellite services and terrestrial equipment. This environment of exponential growth and disruption is characterized by the innovative NewSpace generation, prominently exemplified by the operations of SpaceX and Starlink. Motta et al. [11] refer that by 2032, 26,104 satellites weighing less than 500 kg, known as SmallSats, will be launched, providing extensive connectivity and innovation, including global internet access. Therefore, developing tools to facilitate access to space through microgravity programs is a significant resource.

This paper presents the MicroGravity Explorer Kit's (MGX) design, a multifunctional platform for conducting microgravity experiments aboard suborbital rocket flights. The MGX aims to democratize access to microgravity research, making it accessible to high school students, undergraduates, and private and governmental research institutes. By simplifying the process and reducing barriers to entry, MGX seeks to promote greater participation and innovation in space sciences.

A comprehensive literature review on microgravity experiments is conducted to ensure that the tool is versatile across different scenarios. Based on this review, specific requirements are established, and an architecture for the MGX is proposed. Designed as an open-source platform, the MGX supports various experiments, reducing costs and accelerating development. This makes it accessible even to students in their first year of university or high school. The MGX platform enables researchers to design, execute, and analyze microgravity experiments with greater ease and at a lower cost, encouraging a broader range of investigations and diverse participation in microgravity research. It also facilitates collaboration and knowledge sharing among researchers.

Moreover, the MGX platform has significant implications for developing new technologies and materials. The platform could lead to breakthroughs in fields like materials science and fluid dynamics by enabling researchers to study material and fluid behaviors in microgravity. These advancements could yield practical applications, such as more efficient propulsion systems and novel materials with unique properties.

In the following sections, the context and framework for the development of the MGX will be explored. Section 2 revisits notable microgravity methods, highlighting key achievements and technological advancements. Section 3 presents the context diagram showing how the microgravity experiment interacts with all involved parts in the mission and provides the methodology adopted in the project of MGX. Section 4 presents a retrospective analysis that forms the basis for identifying critical requirements for the MGX. This section also elaborates on the project requirements and proposes the architecture for the MGX, emphasizing its multifunctional capabilities and open-source nature. This section also provides detailed information on the design of the hardware, firmware, and planned mechanical interfaces, offering a comprehensive overview of the technical aspects of the platform. Finally, the conclusion in Section 5 summarizes the contributions and findings of this research, underscoring the potential impact of the MGX on space science education and public engagement.

2. The Microgravity Environment

The microgravity environment, characterized by near-weightlessness, resulting in a state of free fall or floating, occurs as a result of spaceflight and offers a unique platform for conducting scientific investigations across diverse disciplines such as materials science, combustion science, medicine, electronics, and metallurgy. This section provides an overview of methods used to achieve microgravity environments, highlighting the benefits and limitations of each approach. Figure 2 illustrates various methods of achieving microgravity, including orbital flight, sounding rocket, parabolic flight, and drop tower. Concisely, an explanation of the methods used to achieve microgravity is provided as follows.

In the literature, alternative methods such as the one proposed by Siddhardha [12] demonstrate the use of uncrewed aerial vehicles (UAVs) as microgravity platforms, show-

casing effective control and automation strategies, successful microgravity maneuvers, and onboard experiments. Additionally, many other ground-based microgravity simulation methods are discussed in Vashi et al. [13], particularly through Lab-on-a-Chip (LOC) devices, which are an attractive option for simulating microgravity in a controlled laboratory environment. Although this is an interesting and promising approach, the focus here will be on the traditional methods of achieving microgravity listed below.

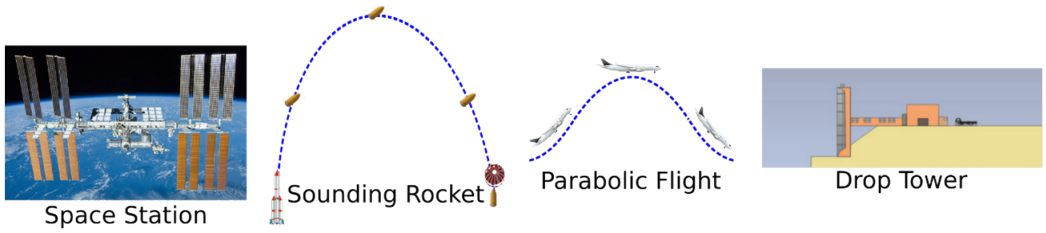


Figure 2. Means of access to the microgravity environment.

2.1. Drop Tower

The drop tower is a means used to create a microgravity environment. Typically, these towers are approximately 100 m tall and can maintain a vacuum of 10^{-4} atm. This setup ensures that an object released from the top of the tower experiences primarily Earth's gravitational field. The duration of microgravity provided by these facilities varies between 4 and 9.3 s [14]. According to Gierse et al. [15], the GraviTower Bremen Prototype, which has been operational since January 2022, can achieve a weightlessness quality of 10^{-4} g. It can perform up to 960 short-term microgravity experiments daily, each lasting 10 s.

As reported by Ferranti et al. [16], free fall towers, or drop towers, offer several advantages for generating a microgravity environment, including their low cost compared to other methods such as orbital flights or sounding rockets, relatively straightforward safety requirements that make them accessible for researchers, and the ability to conduct several tests per day, allowing for multiple experiments to be carried out in quick succession. However, drop towers also have some key limitations. The duration of microgravity is relatively short, ranging from 2.2 s in the NASA Glenn 2.2 Second Drop Tower to 9.5 s in the Drop Tower Catapult System in Bremen. Additionally, as discussed in Belser et al. [17], the microgravity quality in drop towers achieves quality of better than 10-5 g, which is lower than the levels achievable in orbital facilities such as the International Space Station. The Fallturm Bremen, a drop tower at the Center of Applied Space Technology and Microgravity at the University of Bremen in Bremen, Germany, is shown in Figure 3.

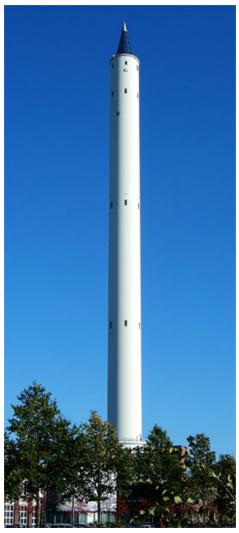


Figure 3. View of the Bremen Drop Tower facility at the University of Bremen, Germany.

2.2. Parabolic Flight

One approach to achieving longer and more frequent periods of microgravity is through parabolic flights aboard aircraft, as illustrated in Figure 2. Although the duration of microgravity is longer than that experienced in the Free Fall Tower, the quality of the environment is lower, typically in the range of 10^{-2} g. One advantage is the ability to perform multiple parabolas during a single flight, each lasting approximately 20 s. Parabolic flights also offer the capability to carry humans, which is essential for training and acclimating individuals to space missions, as discussed by De Witt et al. [18] regarding the physiological effects of microgravity on astronauts. As highlighted by ElGindi et al. [19], with the increase in crewed space missions in recent years and the potential for returning to the Moon and beginning the journey to Mars [20], it has become increasingly essential to understand how the absence of gravitational forces impacts living organisms. This capability extends beyond astronaut training, as highlighted by Pletser [7]. For example, Jirak et al. [21] conducted a study using parabolic flights to investigate the effects of weightlessness and increased gravity on biomarkers associated with heart failure.

During the parabolic flight, as depicted in Figure 4, there are two periods before and after the microgravity phase, each lasting about 20 s, where gravity increases to between 1.5 and 1.8 g, according to ESA [22]. ESA also mentions that up to 96 parabolic maneuvers can be performed in a single flight, utilizing a cargo compartment with 20 × 5 × 2.3 m dimensions. Thus, parabolic flight is characterized by its high payload capacity, repeatability, and ability to conduct experiments with humans despite the disadvantage of shorter microgravity duration. However, it is longer than that of a drop tower. There is also the issue of the lower-quality microgravity environment.

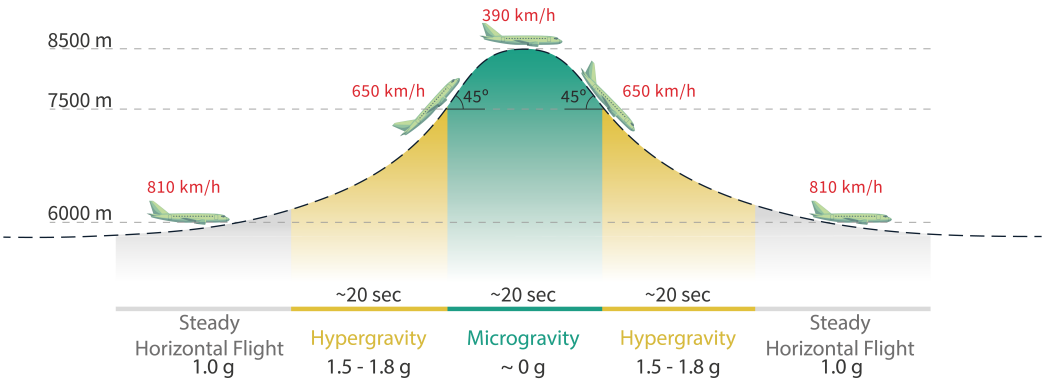


Figure 4. Typical parabolic flight profile.

2.3. Orbital Flight

Another method for conducting experiments in a microgravity environment is through orbital flights, such as those provided by space stations like the International Space Station (ISS) and Tiangong (China). These stations are in constant free fall in Earth orbit, providing unlimited time to perform experiments in microgravity. However, this approach has some disadvantages. Firstly, the high cost of launching experiments to the space station is a significant barrier. Additionally, experiments destined for these stations must undergo rigorous qualification processes to minimize risks to crew members and station facilities.

Numerous studies have been conducted on space stations. For example, Camberos et al. [23] demonstrated through an ISS experiment that being in space caused cardiovascular cells to adopt a gene expression pattern similar to early-stage stem cells, impacting their growth, survival, and development, which could inform future space missions and technologies benefiting life on Earth. Recently, Yoshida et al. [24] reported the "Stem Cells" project led by the Japan Aerospace Exploration Agency (JAXA), where mouse ES cells were stored on the ISS for 1584 days inside the Minus Eighty Degree Laboratory Freezer for ISS (MELFI). After returning to Earth, the cells were thawed and cultured, and their gene expressions were examined using RNA sequencing to study their reaction to extended exposure to space radiation. The

analysis revealed heightened expression of genes linked to cell cycle arrest and DNA repair, suggesting a response to accumulated DNA damage caused by space radiation.

Moreover, some microgravity research studies focus on the long-term effects of microgravity on the human body, making this type of platform ideal for such investigations. For example, in experiments conducted aboard the ISS, Tran et al. [25,26] examined how space microgravity impacts oligodendrocyte progenitors (OLPs)—a critical type of brain cell involved in forming the myelin sheath that insulates nerve fibers and facilitates electrical signal transmission—as they adapted to Earth's gravity after nearly 40 days in space. As we approach a new era of space exploration with manned missions to Mars and the Moon [10], understanding the effects of microgravity on the human body becomes a matter of utmost priority.

In the field of plant biology, Vandenbrink and Kiss [27] highlighted that experiments in plant space biology on the ISS have provided valuable contributions to our understanding of the physiology, genetics, and genomics of plants grown under microgravity conditions. Similarly, Shen et al. [28] reported a seed fixation strategy for efficient seed germination in space. Zhao et al. [29] also discuss various other significant contributions to microgravity research, including microgravity fluid physics, microgravity combustion science, space materials science, space fundamental physics, space biotechnology, and relevant space technology applications, emphasizing orbital flights as a primary means for creating microgravity environments.

Despite the advantages, the main limitation of this type of access to the microgravity environment is the small number of flights and the limited number of experiments that can be carried out. Even so, for long-term studies, this is the best solution. Figure 5 shows, in the left panel, the external view of the International Space Station, while the right panel highlights chili peppers growing under LED lights, emphasizing their role in sustainability and success in space farming [30].



Figure 5. External view of the International Space Station (**left** panel). An experiment was conducted in a microgravity environment on the ISS at the horticultural lighting project (**right** panel).

2.4. Suborbital Flight

Silva and Perondi [31] highlighted that sounding rockets in suborbital flights have been utilized for scientific and technological research since the late 1950s, marking the beginning of the space age. Recent examples of experiments include Ishizuka et al. [32], who demonstrated the formation of alumina (Al_2O_3) particles around oxygen-rich evolved stars using rocket-based microgravity experiments. These studies revealed specific infrared features that aid in understanding stellar dust formation. This is an example of how microgravity experiments can advance space science research. Another significant work by Amselem [33] focused on drug research involving membrane transport, gene expression, cell physiology, and biotechnology. With the advancement of small launchers, more suborbital flights using sounding rockets are anticipated shortly, as discussed by

Amselem [33]. Villas-Boas et al. [34,35] also highlighted these advancements, noting the adaptation of such vehicles to launch CubeSats.

These developments underscore the importance of using rockets for microgravity studies and their potential for scientific advancements in various fields. For users who do not have the resources for an orbital flight but need the space environment for their experiments, suborbital flights provide a viable option to achieve microgravity [36]. These flights offer longer and higher-quality microgravity than parabolic flights and drop towers. Additionally, suborbital flights can carry sophisticated electronic instrumentation, as demonstrated in the solidification furnace experiment by Toledo et al. [5] and the compressor proposal by Pinto et al. [37].

During suborbital flights, the payload, housing the experiments, ascends towards the apogee, as depicted in Figure 6 for a generic mission based on the events described by Simões et al. [38]. First, there is the propulsive phase, which starts with the rocket launch. During this phase, the rocket, which typically has one stage (VS-30) or two stages (VSB-30), is stabilized by the roll induced by the vehicle's fins [39]. After the propulsive phase, when the payload reaches an altitude above approximately 65 km in near-vacuum conditions with minimal aerodynamic forces, it is still subject to centrifugal force from the stabilizing rotation. A yo-yo system is activated to reduce the vehicle's rotation significantly. After that, the payload separates from the rest of the vehicle. From this point onward, the payload retains residual rotation, which a cold gas (nitrogen) control system cancels. Above 100 km, aerodynamic forces become negligible, allowing the payload and onboard experiments to experience a microgravity environment on the order of 10^{-4} g [40]. This condition persists until the payload begins its descent, re-entering the Earth's atmosphere and experiencing intense deceleration. During this phase of the flight, the parachute opening sequence takes place, followed by the payload recovery process. Data from the vehicle's sensors and experiments is transmitted throughout the flight to the ground telemetry station.

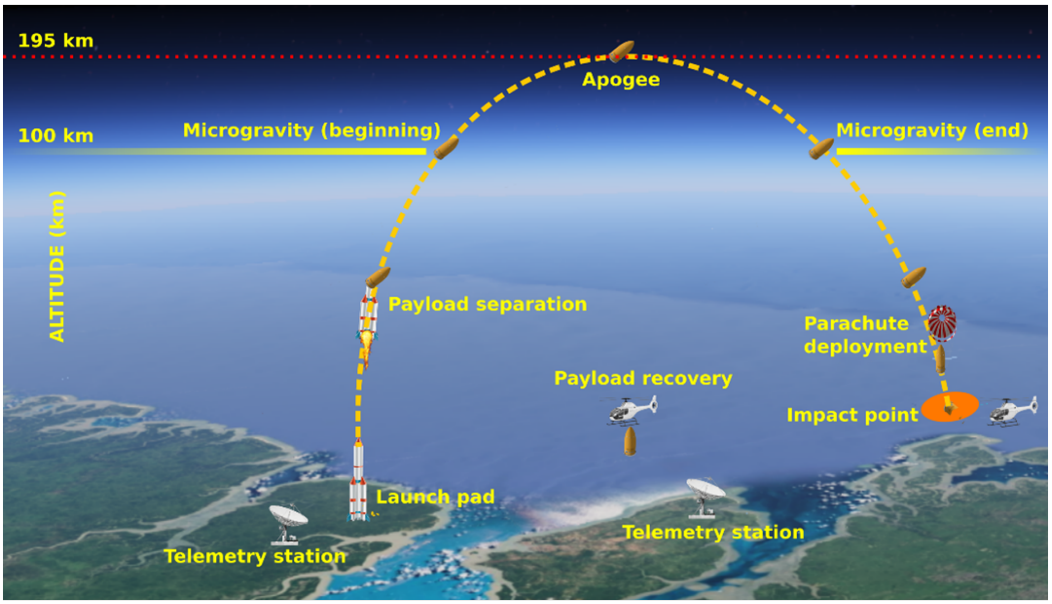


Figure 6. Illustration of a Rocket-Based Suborbital Flight Profile for Performing Microgravity Experiments.

3. Methodology

Sounding rockets are typically launched from rocket launch sites equipped with facilities for preparing and launching rockets into space. These facilities include launch pads, concrete pads, propellant storage and transfer systems, and vehicle assembly buildings where rockets are assembled and payloads, such as microgravity experiments, are integrated. The experiments are incorporated into the onboard avionics and monitored via telemetry and umbilical cables at the blockhouse. While details of the flight of a suborbital vehicle are shown in Figure 6, Figure 7 complements this by focusing on the

experiment, providing a context diagram of the microgravity experiment, the rocket, and the launch center.

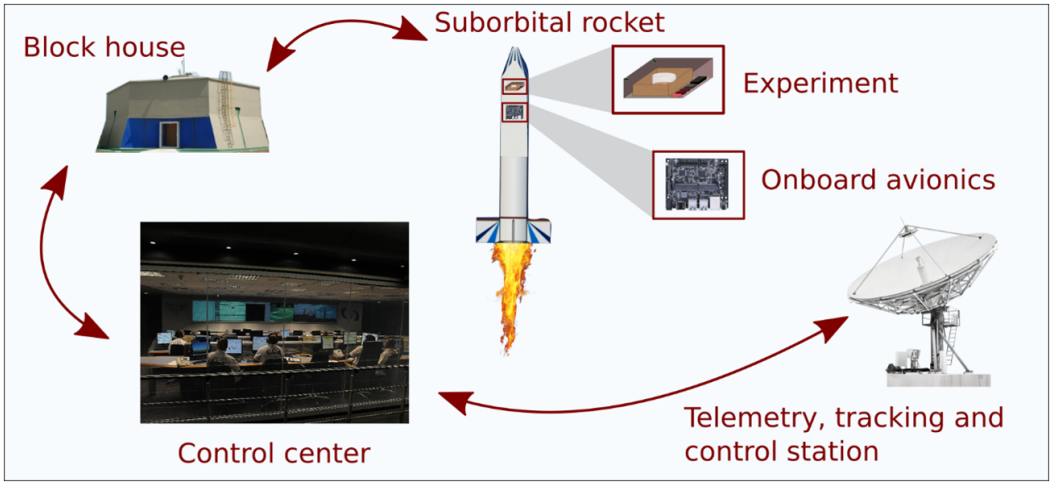


Figure 7. Diagram of the microgravity experiment, the rocket, and the launch center.

When a rocket is positioned on the launch pad, prepared for liftoff, it is typically monitored and operated by rocket operators in a blockhouse during the countdown. Many procedures are carried out during a launch campaign, as discussed by Fugivara et al. [41]. Control centers, where mission control managers make decisions and command launches, play a critical role. After the launch, all teams monitor the flight using the range safety and communication systems, including flight termination systems to destroy the rocket, if necessary, and radar and telemetry tracking systems to monitor the rocket flight performance and the experiment. At the end of the flight, the payload is recovered to extract the experiment for post-flight analysis on-site.

Silva and Perondi [31] propose a tailored project life cycle for Brazilian sounding rocket missions based on the European Cooperation for Space Standardization (ECSS) standards. They begin by characterizing sounding rocket missions as projects and outline the generic life cycle recommended by ECSS for typical space missions. Since sounding rocket missions are inherently more straightforward than traditional space missions, the authors argue that adapting the ECSS life cycle to these missions is a logical step.

The shortened life-cycle balances maintain project management standards and ensure mission reliability for Brazilian-sounding rocket missions. They suggest this framework could be a foundation for updating existing guidelines or creating new protocols for such missions. This methodology was applied to the MGX design, where phases 0 and A are retained in full, B and C are merged, and the D phase comprises manufacturing, assembly, integration, and testing. At the same time, E/F is Launching and closeout, as detailed in Table 1.

The next section outlines this life cycle, beginning with a literature review that addresses the stages of mission analysis. Based on this, the MGX requirements will be established. Subsequently, an architecture for the MGX will be proposed, followed by hardware and software implementation details.

Table 1. Project Life cycle adopted for MGX.

Phase	Description
Phase 0—mission analysis	the mission objectives and high-level requirements are established in this phase. The expected outcomes of the potential missions will be studied, focusing on the questions the experiment may aim to answer. This phase will further refine by the MGX user as they tailor the experiment to their specific needs.
Phase A—feasibility	In this phase, the Concept of Operations (ConOps) will be established. Architectural studies and the selection of a viable architecture will be defined based on the high-level studies conducted in Phase 0. The concept of models (qualification, acceptance, etc., or protoflight) and methodologies for verifying the high-level requirements will be proposed.
Phase B/C—design	In Phase B/C, the mission requirements, constraints, and specifications are refined to enable the detailed design and verification of the MGX.
Phase D—manufacturing, assembly, integration, and testing	In this phase, with the design already approved, the manufacturing and verification of the MGX are completed. The MGX is now ready to be integrated with the rocket.
Phase E/F—launching and mission closeout	In this phase, the MGX is integrated into the service module of the suborbital rocket and will be launched. When applicable, recovery.

4. MGX Design

The initial step involved compiling a detailed list of experiments from the literature to ensure its versatility and flexibility as a tool for developing microgravity experiments. This enabled classifying experiments based on their technological types and instrumentation specifics. Subsequently, this survey established the requirements for developing the MGX project, which are detailed in this section.

4.1. Review of Microgravity Experiments

As discussed in numerous studies in the previous section, one of the most active areas in microgravity research involves biological investigations and measurements (e.g., Demets [42]; Cazzaniga et al. [43], 2016; Kopp et al. [44], 2018; Aventaggiato et al. [45]; Grimm [46]). Analyzing biological images in microgravity might be important, for example, for understanding how this environment affects living organisms. Therefore, developing a platform capable of automating the capture, processing, and real-time analysis of biological images during microgravity experiments represents a significant advancement proposed in this work.

Additionally, as noted by Kirchhartz et al. [47], sounding rocket platforms have been utilized for various technological experiments, including hypersonic flights. Another common application of such vehicles is for ionospheric studies, where the microgravity environment is incidental rather than the primary focus. Evaluating experiments of this mission profile is essential here. Therefore, both technological test flights and upper atmosphere studies, while not reliant on microgravity for their outcomes, are relevant experiments related to the research being assessed in this study. The MGX design is not confined to applications in biology, ionospheric physics, materials science, and space technologies alone. Still, it could also serve as a versatile tool for research in other fields.

This section will review a series of studies from the literature, detailing their results and the specifics of their experimental implementation. Despite analyzing experiments from various microgravity methods, the focus is on identifying trends in instrumentation and common characteristics that the MGX can incorporate into its design. Identifying commonalities among these experiments, including their primary goals and characteristics, will be fundamental in establishing the design parameters of the MGX. Table 2 lists 20 experiments from the literature on microgravity experiments. Each experiment is accompanied by details of its onboard sensors and classified into four additional categories: hypersonic (H), microgravity (M), parabolic flight (PF), or drop tower (DT). Table 2 also indicates whether the experiment required actuator systems, cameras for imaging, and decision-making

capabilities. The legend at the bottom of Table 2 provides information about the classifiers. The column's legend is presented as follows: The "Class of environment experiment" is represented by column (C) and can be designated as Hypersonic (H), Microgravity rocket flight (M), Suborbital rocket flights (SO) or Drop Tower (DT). The column (A) indicates whether the work involves actuators (Yes/No). Column (CM) denotes the presence of cameras for the work (Yes/No). Finally, column (DM) indicates whether the work involves real-time decision-making (Yes/No).

Table 2. List of microgravity experiments analyzed and their main characteristics.

Experiment Title	Sensors	C	A	CM	DM
A student experiment to investigate the sloshing of magnetic liquids in microgravity, Romero-Calvo et al. [48].	• Current • Magnetometer • Accelerometer • Infrared Distance	M	Yes	Yes	No
The CFVib Experiment: Control of Fluids in Microgravity with Vibrations, Fernandez et al. [49].	• Accelerometer	M	Yes	No	No
Solidification of Eutectic Alloys in Microgravity, Toledo et al. [5,6].	• Temperature • Liquid Flow	SO	No	No	No
Experimental testing of mini heat pipes under microgravity conditions aboard a suborbital rocket, Paiva et al. [50,51].	• Temperature	SO	Yes	Yes	No
Properties of Wave Propagation in a Gel-type Belousov–Zhabothinsky Reaction under Micro-gravity, Hanke et al. [52].	• Temperature • Pressure	SO	Yes	No	No
Rocket in situ observation of equatorial plasma irregularities in the region between E and F layers over Brazil, Savio Odriozola et al. [53]	• Langmuir Probe	SO	No	No	No
HIFIRE: An international collaboration to advance the science and technology of Hypersonic Flight, Bowcutt et al. [54].	• Pressure • Temperature • IMU • GPS	H	No	No	No
Propellant Mass Gauging in a Spherical Tank under Micro-Gravity Conditions Using Capacitance Plate Arrays and Machine Learning, Chowdhury et al. [55].	• Capacitance	M	No	No	Yes
Control of growth interface shape during InGaSb growth by vertical gradient freezing under microgravity and optimization using machine learning, Ghritli et al. [56].	• Temperature • Liquid Flow	M	No	No	Yes
A pulsating heat pipe for space applications: Ground and microgravity experiments, Mangini et al. [57].	• Temperature • Pressure	SO	Yes	Yes	No
Experimental Investigation of In-Tube Condensation in Microgravity, Azzolin et al. [58].	• Temperature • Pressure	SO	Yes	Yes	No

Table 2. *Cont.*

Experiment Title	Sensors	C	A	CM	DM
Free Collisions in a Microgravity Many-Particle Experiment. I. Dust Aggregate Sticking at Low Velocities, Weidling et al. [59].	• N/A	M	Yes	Yes	No
Microgravity experiments of fuel droplet evaporation in sub- and supercritical environments, Nomura et al. [60].	• Temperature	DT	No	Yes	No
Experimental Investigation of Single Bubble Nucleate Boiling in Microgravity, Nejati et al. [61].	• Temperature • Pressure • Coriolis Flow	SO	No	Yes	No
MEMS Microgravity Measurement Module with Nano-g/HzNoise Floor for Spaceborne Higher-Level Microgravity Scientific Experiment Applications, Wang et al. [62].	• Accelerometer	SO	No	No	No
Precise Measurement Method of Carrier Motion State in Microgravity Environment, Liu et al. [63].	• IMU	DT	No	Yes	No
Design and Results of an Experiment to gather Data on the Motion of a Non-rigid Body in Microgravity, Blazejczyk et al. [64].	• IMU	DT	No	No	No
Suborbital Payload Testing Aboard Level 3 Rocket Research Platform, Amberkar et al. [65].	• Radiation • Acceleration • Pressure • Temperature • Humidity	SO	No	No	No
Propellant management in microgravity: further analysis of an experiment flown on REXUS-14, Strobino et al. [66].	• Accelerometer	M	Yes	Yes	No
SOAREX-8 Suborbital Experiments 2015—A New Paradigm for Small Spacecraft Communication, Stone et al. [67].	• Temperature • Pressure • Accelerometer	M	No	No	No

4.2. Requirements

Based on the review of works summarized in Table 2, as well as studies related to suborbital rocket avionics and launch operations [34,37,38,40,41,68–70], a set of requirements was established for the MGX. The MGX aims to serve as a platform that simplifies the design of microgravity experiments for researchers and students. Despite its goal of facilitating development, the platform must be compatible with the avionics on board rockets, with the MGX being specifically dedicated to unmanned flights and its design fully compatible with the service module of sounding rockets. Therefore, elaborating these requirements seeks to uphold these premises while maintaining the open-source concept. This means that its developments will be available, modifiable, and distributable within the academic community, enhancing collaborations and providing tools for data acquisition, analysis, and content management based on MGX.

A list of requirements was compiled based on the microgravity experiments in the literature review, summarized in Table 2. The requirements were written based on standard IEEE 29148 [71], which addresses requirements engineering. It defines the process as involving discovery, elicitation, development, analysis, verification, validation, communication, documentation, and requirements management as outlined in standard IEEE 29148 [71]. These activities aim to produce a comprehensive requirements document. According to

dos Santos and Marques [72], aerospace projects demand a strong requirements document to minimize sudden decisions.

Table 3 presents the requirements for MGX hardware, software, and the operational environment. These requirements encompass the system's functional, interface, operational, and environmental aspects. Functional requirements describe the specific behaviors and capabilities of the system, outlining what the MGX should achieve. Interface requirements detail the system's interactions with other systems or components, specifying communication standards and protocols, connector types, and data formats to ensure compatibility and integration. Operational requirements address the system's conditions, including compliance with EMI/EMC (Electromagnetic Interference)/(Electromagnetic Compatibility) standards. Environmental requirements define the external conditions the system must withstand, such as temperature ranges, vibration, and other factors critical for its successful operation. These requirements ensure the MGX system fully integrates and functions within the operational contexts discussed in Figures 6 and 7.

Table 3. List of MGX Requirements.

REQ-[ID]	Description
REQ-1	The MGX shall be powered by a main power supply.
REQ-2	The main power supply shall provide 28 Volts ±4 Volts.
REQ-3	The main power supply shall provide 5 Ampere.
REQ-4	The main power reference shall be connected to the device case through a 100 KΩ path.
REQ-5	The MGX shall generate interval voltages.
REQ-6	The MGX shall generate an internal voltage of +3.3 Vdc.
REQ-7	The +3.3 Vdc shall be available through a D-Sub 15 power socket connector.
REQ-8	The +3.3 Vdc shall have the reference isolated from other references.
REQ-9	The MGX shall generate an internal voltage of +5 Vdc.
REQ-10	The +5 Vdc shall be available through a D-Sub 15 power socket connector.
REQ-11	The +5 Vdc shall has reference isolated from other references.
REQ-12	The MGX shall generate an internal voltage of +12 Vdc.
REQ-13	The +12 Vdc shall be available through a D-Sub 15 power socket connector.
REQ-14	The +12 Vdc shall have the reference isolated from other references.
REQ-15	The MGX shall contain one inertial measurement unit (IMU).
REQ-16	The IMU shall provide a gyroscope with a range of ±2000°/s.
REQ-17	The IMU shall provide an accelerometer ranging from ±16g.
REQ-18	The MGX shall contain two cameras.
REQ-19	The camera shall have a USB (Universal Serial Bus) interface.
REQ-20	The camera shall support 4K images.
REQ-21	The MGX shall contain one pressure sensor.
REQ-22	The pressure sensor shall range from 0 to 40 KPa.
REQ-23	The MGX shall contain one temperature sensor.
REQ-24	The MGX temperature sensor shall withstand temperatures ranging from −10 °C to 85 °C.
REQ-25	The MGX shall withstand a random vibration profile of 0.1 g^2/Hz from 20 Hz to 2000 Hz, with 10 grms, in 3 axes.

Table 3. *Cont.*

REQ-[ID]	Description
REQ-26	The MGX shall withstand shocks of 40 g amplitude for 110 milliseconds, following a half-sine waveform.
REQ-27	The MGX shall withstand shocks of 40 g amplitude for 110 milliseconds, following a half-sine waveform.
REQ-28	The MGX shall not compromise the EMI/EMC vehicle networks.
REQ-29	The MGX shall provide 2 UART (Universal Asynchronous Receiver/Transmitter) ports.
REQ-30	The UART1 port shall adhere to the RS-232 standard.
REQ-31	The UART1 shall be available through a D-Sub 9 socket connector.
REQ-32	The UART2 port shall adhere to the RS-422 standard.
REQ-33	The UART2 shall be available through a D-Sub 9 socket connector.
REQ-34	The UARTs shall be isolated.
REQ-35	The UARTs baud rate shall be configured via software.
REQ-36	The MGX UARTs shall be programmable and capable of communicating at 9600 bps, 14,400 bps, 19,200 bps, 38,400 bps, 57,600 bps, and 115,200 bps.
REQ-37	The MGX shall provide 16 General Purpose Input/Output (GPIO).
REQ-38	The GPIOs shall be available through a D-Sub 25 socket connector.
REQ-39	The GPIOs shall operate at TTL (Transistor–transistor logic) levels.
REQ-40	The MGX shall provide 2 I2C port.
REQ-41	The I2C port shall be available through a D-Sub 9 pin connector.
REQ-42	The I2C shall operate up to 1 MHz
REQ-43	The MGX shall provide 12 analog channels.
REQ-44	The analog channels shall operate at 0–5 Vdc.
REQ-45	The analog channels shall be available through a D-Sub 25 pin connector.
REQ-46	The Analog channel sample rate shall be configured via software.
REQ-47	The MGX shall support SSD (solid-state drive) M.2 NVMe storage expansion.
REQ-48	The MGX shall record the collected data and video in non-volatile memory.
REQ-49	The non-volatile memory shall have the capacity of 500 G Byte.
REQ-50	The MGX shall operate in a temperature environment ranging from −40 °C to +75 °C.
REQ-51	When powered on, the MGX shall immediately begin operating according to its programmed sequence.
REQ-52	The MGX shall be developed using a high-performance computer (HPC) equipped with a GPU.
REQ-53	The MGX shall be capable of making autonomous decisions during flight.
REQ-54	The HPC (High-Performance Computer) shall support Machine learning frameworks.
REQ-55	The HPC (High-Performance Computer) vendor should provide a software development kit (SDK).
REQ-56	The MGX shall consist of two main modules: electronic processing and experimental modules.
REQ-57	The MGX electronic processing module dimension shall be 1U (10 cm × 10 cm × 10 cm).

Table 3. *Cont.*

REQ-[ID]	Description
REQ-58	The experiment module shall be developed by the experimenter, adhering to the rocket's mechanical interface requirements.
REQ-59	The dimensions and shape of the experiment module must comply with the specified interface constraints to ensure proper integration with the rocket.
REQ-60	The MGX shall be four fixing points.
REQ-61	The fixing points shall support the M6 bolt.
REQ-62	The MGX shall be capable of connecting via Ethernet for ground tests.
REQ-63	The MGX shall collect data during System operation for instrument calibration purposes.
REQ-64	The MGX shall withstand random vibration levels of up to 6 grms.

4.3. Architecture

From the rocket-based suborbital flight profile depicted in Figure 6 and the context diagram of the microgravity experiment with the rocket and launch center illustrated in Figure 7, combined with the requirements outlined in Table 2, it is possible to establish a general architecture for the MGX, as presented in Figure 8. Furthermore, the experiments listed in Table 2 could theoretically be adapted to utilize the MGX device. This demonstrates the versatility of the proposed device and highlights its potential to facilitate the development of microgravity experiments, particularly for students who may face challenges with more complex tools, thus democratizing access to space.

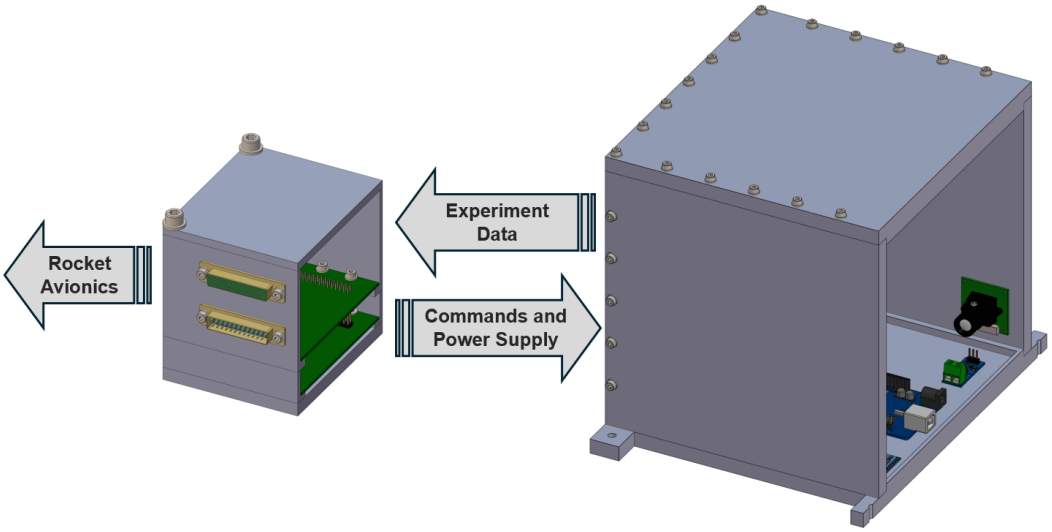


Figure 8. Illustration of the MGX architecture divided into two parts. On the left-hand side is the electronic processing module with dimensions of 1U. On the right-hand side is an example of the experimental module, which can be customized in size according to specific research demands, containing sensor instrumentation and cameras.

The analysis of Figure 8 establishes the concept of the MGX divided into two distinct parts as specified by REQ-56, REQ-57, and REQ-58 in Table 3. The first part comprises the electronic processing module (left module in Figure 8), while the second part (right module in Figure 8) corresponds to the experiment module itself. In this two-part concept, the processing module can be standardized, while the experiment module can be customized according to the specific needs of each experiment, as outlined in REQ-58 and REQ-59.

This modular architecture enhances vehicle integration by ensuring compatibility between the electronic processing module and the rocket's avionics. Simultaneously, the

experiment module's customizable nature empowers researchers to tailor experiments to specific scientific requirements. The connection between these modules facilitates sensor readings and experiment control. All sensors, cameras, and actuation systems will be housed within the experiment module, while the processing module manages tasks such as sensor and camera acquisition, experiment actuation control, and communication with rocket avionics for telemetry data transmission. The electronic processing module is designed for 3D printing. It is suitable for any printer with a print table larger than 200x200 mm, thereby maintaining the concept of making experimentation more accessible, especially for students. The electronic processing module enclosure has been designed to withstand the specified random vibration outlined in REQ-64 [70] while also preventing transmission to the internal components.

4.4. Hardware Implementation

Figure 9 illustrates the schematics of the hardware of the onboard electronic processing module. The central piece for data processing is the NVIDIA Jetson Orin Nano board, a computing module designed for a wide range of embedded and edge applications, including AI computing. This board features a 6-core Arm Cortex-A78AE CPU and an NVIDIA Ampere GPU with up to 1024 cores and Tensor Cores. With this hardware as the core of the processing module, it is possible to ensure the acquisition of large amounts of experimental data, as well as data from pressure, inertial sensors, and 4K camera images. Based on this hardware, the requirements REQ-20, REQ-21, REQ-30, REQ-37, REQ-41, REQ-43, REQ-45, REQ-47, and REQ-49 are fulfilled. Additionally, it has an interface for reading I2C instrumentation from the experiment module's sensors (Figure 10), as well as TTL I/Os for reading or actuation. The processing capacity also supports H.265 data compression REQ-49) and machine learning algorithms (REQ-55) for real-time pattern recognition and feature extraction from images, for example. This hardware component is responsible for all communication between the experiment and the blockhouse or telemetry. Figure 8 depicts the hardware architecture of the module with all its interfaces.

In the electronic processing module, three sensors are attached: the IMU, pressure, and temperature sensors. These sensors serve basic functions: the IMU provides altitude and attitude data during flight, the temperature sensor monitors the Jetson Nano's heat sink, and the pressure sensor offers a rough estimate of altitude while primarily identifying transient periods in the vacuum of space. One serial UART is used to transmit serial data to the telemetry system on board the rocket. This module also includes voltage regulation sources to meet the requirements specified in REQ-2, REQ-3,. REQ-6, REQ-7, REQ-8, REQ-9, REQ-10 and REQ-13. There is also an Ethernet connection for ground tests (REQ-62). The module also includes an option for recovery flights, featuring an M.2 NVMe bus connection capable of connecting to an SSD (REQ-48, REQ-49, REQ-50). This setup allows for recording experiment data and video throughout the flight.

The interface requirements address how the MGX interfaces with the experiment. To fulfill these requirements, the REQ-1, REQ-7, REQ-10, REQ-13, REQ-19, REQ-31, REQ-33, REQ-38, REQ-41, REQ-45, and REQ-62 specify the type of interface expected. Figure 9 shows the MGX's connectors distribution.

In the diagram in Figure 9, there are interfaces with the experiment module (Figure 10), providing the experiment designer with flexibility in the project and enabling data acquisition in various ways. The data acquisition options on this hardware include USB ports for connecting 4K cameras, an I2C bus for reading sensors, a UART for acquiring serial data, 12 analog input channels with a range of 0 to 5 V, and 16 GPIO pins that can be used to control the experiment or to read discrete data in the TTL standard.

As mentioned earlier, the experiment module is designed to be adaptable to the experimenter's specific needs while adhering to the rocket integration constraints. Figure 10 illustrates the schematic of electronic interfaces between the experiment module and the electronic processing module (Figure 9). Depending on the project requirements, interface connectors will be selected accordingly. Figure 10 elucidates the capabilities for

multiple ways to monitor the experiment, such as I2C sensors, switches, analog sensors, serial communication via UART (RS-232 or RS-422), and the transmission of data from cameras, including up to 4k resolution, to the electronic processing module. Moreover, if the experiment incorporates actuators, it can receive TTL commands to activate them.

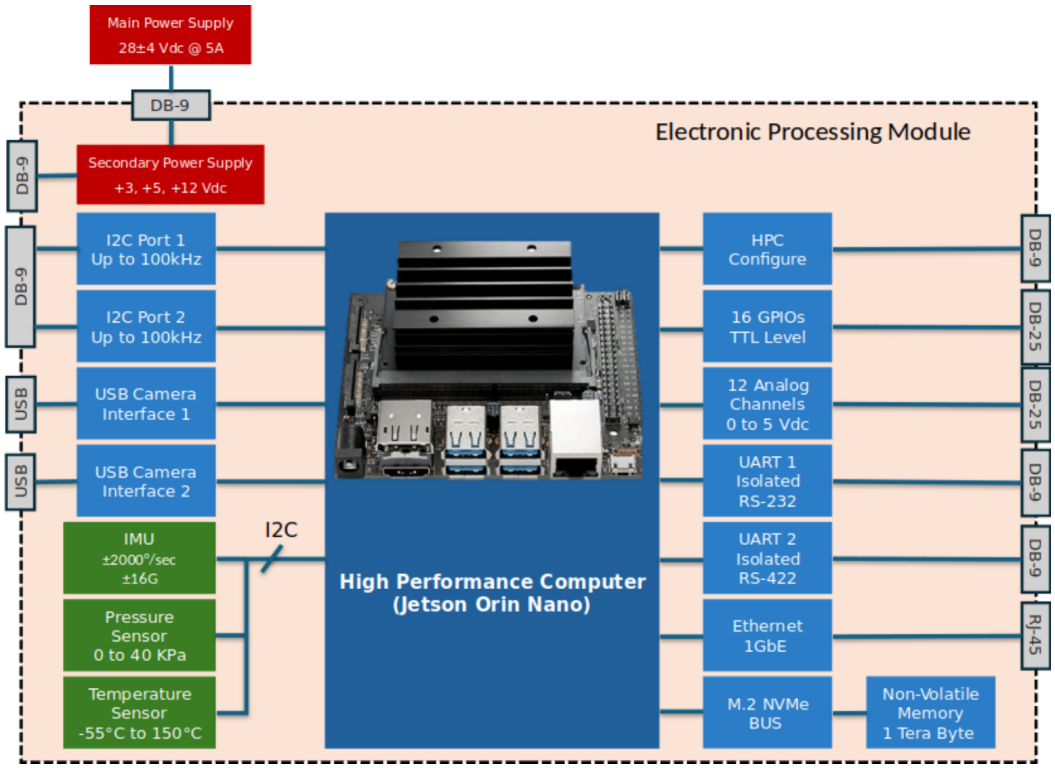


Figure 9. Hardware schematics of the electronic processing module.

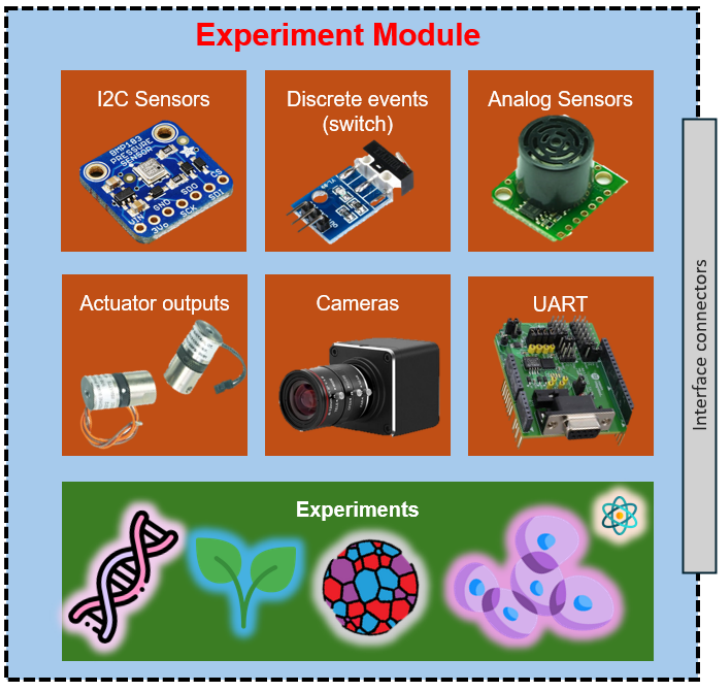


Figure 10. Illustration of electronic sensor capabilities inside the experiment module, including I2C, analog sensors, UART, and 4K camera inputs, besides actuators.

4.5. Software Implementation and Functionality

According to requirements REQ-53 to REQ-56, the MGX must utilize a high-performance computer (HPC) with a GPU capable of autonomous decision-making during flight. It should support machine learning frameworks and provide a software development kit (SDK). For these reasons, the NVIDIA Jetson Nano platform was selected. These specifications enable the MGX to handle heavy processing loads, a defining characteristic of this project that facilitates complex experiments despite its straightforward architecture. This section explores and discusses software implementation possibilities for the MGX. In [46], the original contributions to medical applications emerging from microgravity research were highlighted, and many of the studies described in this paper could benefit from using the MGX. According to REQ-19, REQ-22, REQ-23, and REQ-24, the MGX platform incorporates various sensors, including IMU, temperature, and pressure sensors. Furthermore, MGX must be capable of recording comprehensive flight data for post-recovery analysis (REQ-49). The MGX platform may also perform autonomous decision-making (REQ-54) or execute image processing algorithms, such as pattern recognition based on machine learning algorithms (REQ-55). This subsection describes some software routines related to a Software Development Kit (SDK) (REQ-56), designed to be used on the MGX platform to fulfill these requirements.

The project repository provides routines for reading camera images and sensor data, specifically designed to run on NVIDIA Linux for Tegra (L4T), based on Ubuntu Linux. The MGX's operational codes were developed in C++, while machine learning routines were implemented in Python. In addition to these data and image acquisition routines, the repository also offers routines for data compression using H.265, based on [73]. For more information, please visit this link: "https://github.com/MouraWM/MGX-microgravity-experimental-kit/tree/main (accessed on 21 July 2024)" . Furthermore, the link includes the Interface Control Documents (ICDs) for the connections between the electronic modules that compose the MGX, along with the pin assignment and electrical schematics.

Machine learning plays an important role in automating and enhancing accuracy in data analysis, making it particularly valuable for research conducted in microgravity environments. The behavior of fluids, materials, and biological systems can significantly differ from that observed on Earth, necessitating precise and real-time analysis for scientific advancements [16,46]. The Jetson Nano platform, used in the MGX, enables efficient parallel processing, facilitating rapid and accurate analysis of large data volumes. Implementing ML algorithms on the Jetson Nano involves some stages, from data collection and preprocessing to real-time analysis and decision-making. Equipped with high-resolution sensors and cameras, the Jetson Nano may continuously collect data during microgravity experiments, including high-resolution images and sensor data on temperature, pressure, and IMU. The first step is data preprocessing to ensure it is suitable for analysis [74].

Image data can be preprocessed using libraries like OpenCV and PyTorch. This includes image normalization, noise removal, and transforming images into a format compatible with deep learning models. While deep learning model training typically occurs on powerful workstations or GPU clusters, the Jetson Nano can handle smaller training tasks or fine-tuning pre-trained models. Models like Convolutional Neural Networks (CNNs), U-Net, and Long Short-Term Memory (LSTM) networks can be trained using frameworks such as TensorFlow or PyTorch [75–77]. After training, ML models can be deployed on the Jetson Nano for real-time analysis during suborbital flights. Object detection and classification in images are essential for many studies. Deep learning algorithms like CNNs can identify and classify particles, microorganisms, or cells in high-resolution images. For fluid experiments, image segmentation using the DeepLabv3+ model can identify and track suspended particles, aiding in understanding phenomena like droplet coalescence or bubble formation [75,78].

Image segmentation might be interesting for isolating and analyzing different components within an image. In microgravity, this capability applies to various experimental contexts. For instance, in biological studies, U-Net can segment different types of tissue or

cells, enabling detailed analysis of cell morphology and interactions in microgravity [76]. These algorithms can be implemented in the MGX, processing real-time images and providing immediate results to researchers. Figure 11 shows the process of segmenting cells using U-Net architecture.

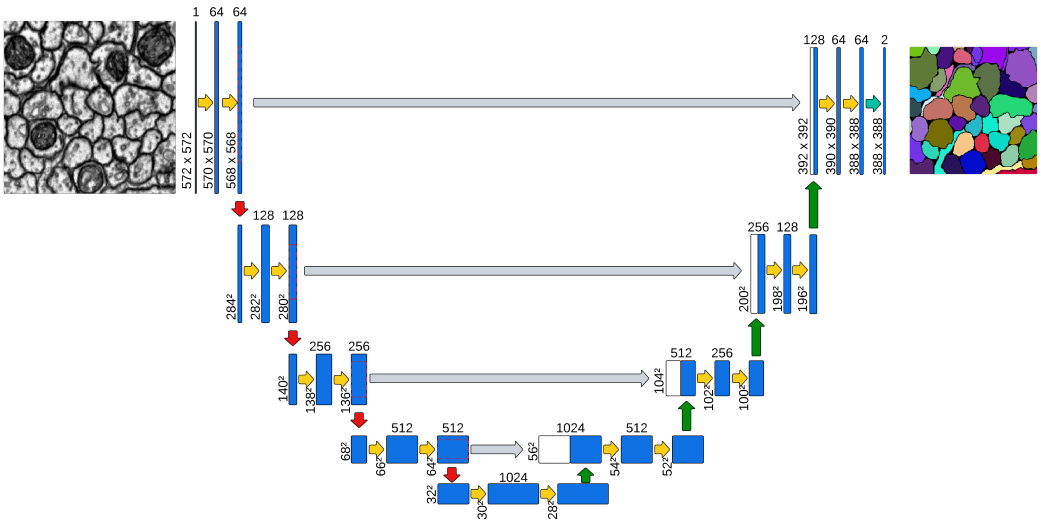


Figure 11. Diagram of U-Net architecture illustrating the process of segmenting cells in biological tissue images.

Tracking movements in microgravity might be important for understanding the dynamic behavior of particles and cells. In this case, deep learning algorithms combining CNNs with LSTM could track the movement of microparticles in fluids, providing detailed data on particle trajectories and velocities [75,77]. This approach is particularly useful in cellular biology experiments, revealing how cells move and interact in a microgravity environment.

Pattern recognition in image data is another powerful ML application in the MGX. Algorithms can detect abnormal patterns or identify specific structures, indicating interesting phenomena or potential problems. For example, deep learning models like YOLO (You Only Look Once) can recognize specific structures in protein crystallization experiments, providing precise data on crystal formation and behavior in microgravity [79].

One of the most significant advantages of using ML in the MGX is automation. ML systems can process and analyze data in real time, allowing immediate experiment adjustments and accelerating results acquisition [74]. Post-flight, automated analysis of large image data volumes can expedite results and insights, saving time and resources for researchers [80].

Modeling and simulation using ML help predict how different experimental conditions affect outcomes, aiding in planning future experiments. ML models can simulate the effects of various microgravity conditions on experimental results, optimizing experiments before flight [74]. Learning algorithms can predict outcomes based on historical data, guiding research and increasing efficiency [80]. This is especially useful in complex experiments, where precise predictions can help identify optimal conditions and reduce the need for repeated trials [46]. Integrating ML with control systems allows for more precise and autonomous experimentation. Computer vision systems integrated with ML can provide automatic feedback to adjust experimental parameters in real time, enhancing accuracy [80]. ML algorithms can control experimental devices like robotic manipulators, ensuring precise and efficient execution based on real-time image analysis [75]. This is particularly beneficial in experiments requiring continuous adjustments, significantly improving data quality and reducing researcher workload [74].

To illustrate MGX's ML capabilities, consider practical examples. One hypothetical application is using ML to monitor sperm motility in microgravity experiments. The study by [81] showed that sperm motility can be affected by simulated microgravity conditions. By analyzing videos of moving sperm, ML algorithms can quantify sperm cell speed and trajectory, providing valuable data on how microgravity impacts reproduction and cellular health. Implementing such analysis on the Jetson Nano enables real-time monitoring and adjustments during space missions, ensuring precise and actionable data collection.

Moreover, ML can analyze cellular respiration and protein content under microgravity conditions. Deep learning algorithms can analyze polarographic data, identifying oxygen consumption patterns associated with mitochondrial activity changes in response to microgravity. Similarly, computer vision algorithms can automate Western blot analysis for protein content, facilitating precise quantification of proteins involved in cellular respiration and cytoskeletal structure. This automation, powered by the MGX, significantly enhances the efficiency and accuracy of biological experiments in microgravity, providing critical insights into cellular functions and adaptations in space [82].

5. Final Remarks

The proposal for the Microgravity Experiment Kit (MGX) aims to contribute significantly to microgravity research, offering a versatile and accessible platform for a wide range of scientific investigations. Microgravity programs are essential for both research and the testing of new technologies, serving as a gateway for careers in the rapidly expanding space industry. This work began with a comprehensive review of all existing means of access to microgravity, followed by an extensive examination of experiments documented in the literature. This review aimed to understand the typical requirements experimenters have for their projects. From this understanding, we established a series of requirements to create a versatile experiment kit adaptable to various demands while fully compatible with sounding rocket instrumentation.

The MGX was thus designed with a modular architecture, divided into two distinct parts: the electronic processing module and the experiment module. The electronic processing module has standardized dimensions of 1U (10 cm $\times$ 10 cm $\times$ 10 cm), while the experiment module is designed to be tailored to the specific needs of each experiment in terms of both size and instrumentation. This flexibility ensures the MGX can accommodate various data acquisition methods, such as I2C sensors, switches, analog sensors, UART (RS-232 or RS-422) communication, and high-resolution camera data transmission, up to 4K resolution. Additionally, the system is capable of generating commands to activate experiment actuators.

Central to the MGX's hardware platform is the Jetson Nano, a powerful computing module capable of running machine learning algorithms for real-time data analysis and decision-making. This capability represents a contribution in space sciences, as it allows the MGX to be programmed to recognize patterns, analyze data, and compress image data from 4K cameras, thereby enhancing the functionality and efficiency of experiments conducted in microgravity.

By developing the MGX, the goal was to create an experiment kit that makes launching experiments into space more accessible to researchers and students, thus promoting STEM education in space science. The MGX's flexible, rocket-compatible yet simple architecture and the availability of basic operating routines ensure that more individuals can participate in and contribute to space research. This inclusivity is fundamental for advancing our understanding of space, fostering scientific progress, and driving technological innovation.

Author Contributions: Conceptualization, A.M. and L.P.S.; methodology, C.R.d.S., W.d.M.M., A.C.P. and M.J.d.S.F.; software, W.d.M.M. and M.J.d.S.F.; requirements, C.R.d.S., W.d.M.M., A.C.P. and L.P.S.; design, W.d.M.M., C.R.d.S., A.C.P., A.M., L.P.S. and M.J.d.S.F.; writing—original draft preparation, W.d.M.M., C.R.d.S., A.C.P. and A.M.; writing—review and editing, L.P.S., M.J.d.S.F. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: CNPq 309389/2021-6.

Data Availability Statement: No data are available at this time, but all code used in this study is available at "https://github.com/MouraWM/MGX-micro-gravity-experimental-kit/tree/main".

Acknowledgments: The authors express their gratitude to Rafael Toleto for providing the furnace experiment images used in Figure 1. They also thank José Bezerra and Valéria Leite for their valuable contributions, discussions, and critiques throughout the development of this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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