Establishing a Multi-Functional Space Operations Emulation Facility: Insights from the Zero-G Lab

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ABSTRACT

This methods paper outlines the development of the Zero-G Laboratory at the University of Luxembourg, a crucial resource for advancing research in space operations. The primary objective of this laboratory is to meticulously simulate operations in the micro-gravity conditions encountered in space, allowing for comprehensive testing of space-related hardware and software before their deployment in the demanding environment of outer space. The key methods employed in establishing this facility include replicating space-representative infrastructure elements such as realistic lighting conditions, epoxy flooring, and robotic systems mounted on rails. The laboratory integrates its hardware and software over a centralized Robot Operating System (ROS) network. Researchers can conduct hybrid emulations, combining robotic systems with pre-modeled software components to simulate intricate orbital scenarios effectively. Furthermore, this paper serves as a practical guide for laboratory construction. The aim of this project is to assist the research community in establishing similar facilities and fostering advancements in space-related research and technology development.

- The laboratory enables 7-Dof motion using rail-enabled robots for testing on-orbit robot operations and validation of spacecraft motion.
- The flat epoxy floor allows the operation of air-bearing floating platforms to emulate frictionless free-floating and free-flying spacecraft motion in 3-Dof.
- Provides a test facility to experiment and validate various Guidance Navigation and Control algorithms and space operations with feedback from perception, Motion Capture System, and any other custom navigation system including vision cameras in space-type lighting.

Related research article

This methods article supports an original research article “Zero-G Lab: A Multi-Purpose Facility for Emulating Space Operations” [1]. DOI: 10.1016/j.jsse.2023.09.003

Specifications Table

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Table 1
Specifications Table

Subject area	Engineering
More specific subject area	Aerospace Engineering
Name of the method	Development of space operations emulation facility
Name and reference of original method	Zero-G Lab: A multi-purpose facility for emulating space operations https://doi.org/10.1016/j.jsse.2023.09.003
Resource availability	N/A

Method Details

This paper outlines the procedural steps taken in the establishment of the Zero-G Lab — a versatile and multifunctional facility designed to replicate a wide array of in-orbit operations across diverse orbital scenarios [2–6]. This emulation is achieved through the integration of various system components, both software and hardware. Such a setup allows the testing of perception algorithms, Guidance Navigation and Control (GNC) systems, robotic interaction, path planning, etc.

The visual representation of the Zero-G Lab's CAD model is depicted in Fig. 1, representing the envisioned design. Through meticulous planning and systematic construction of its subsystems, the current state of the lab is illustrated in Fig. 2. This document provides a comprehensive account of the insights gained from the lab construction process, along with detailed information about the utilized subsystems.

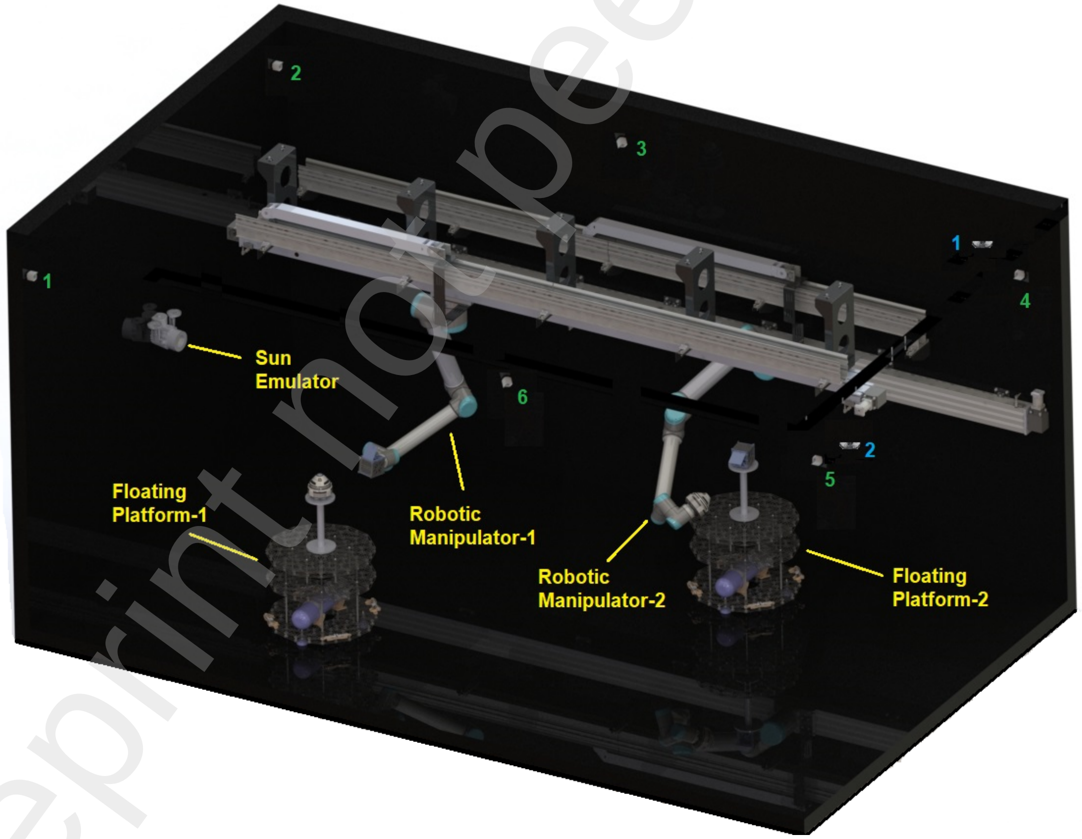

Figure 1: Zero-G Lab's CAD model render.

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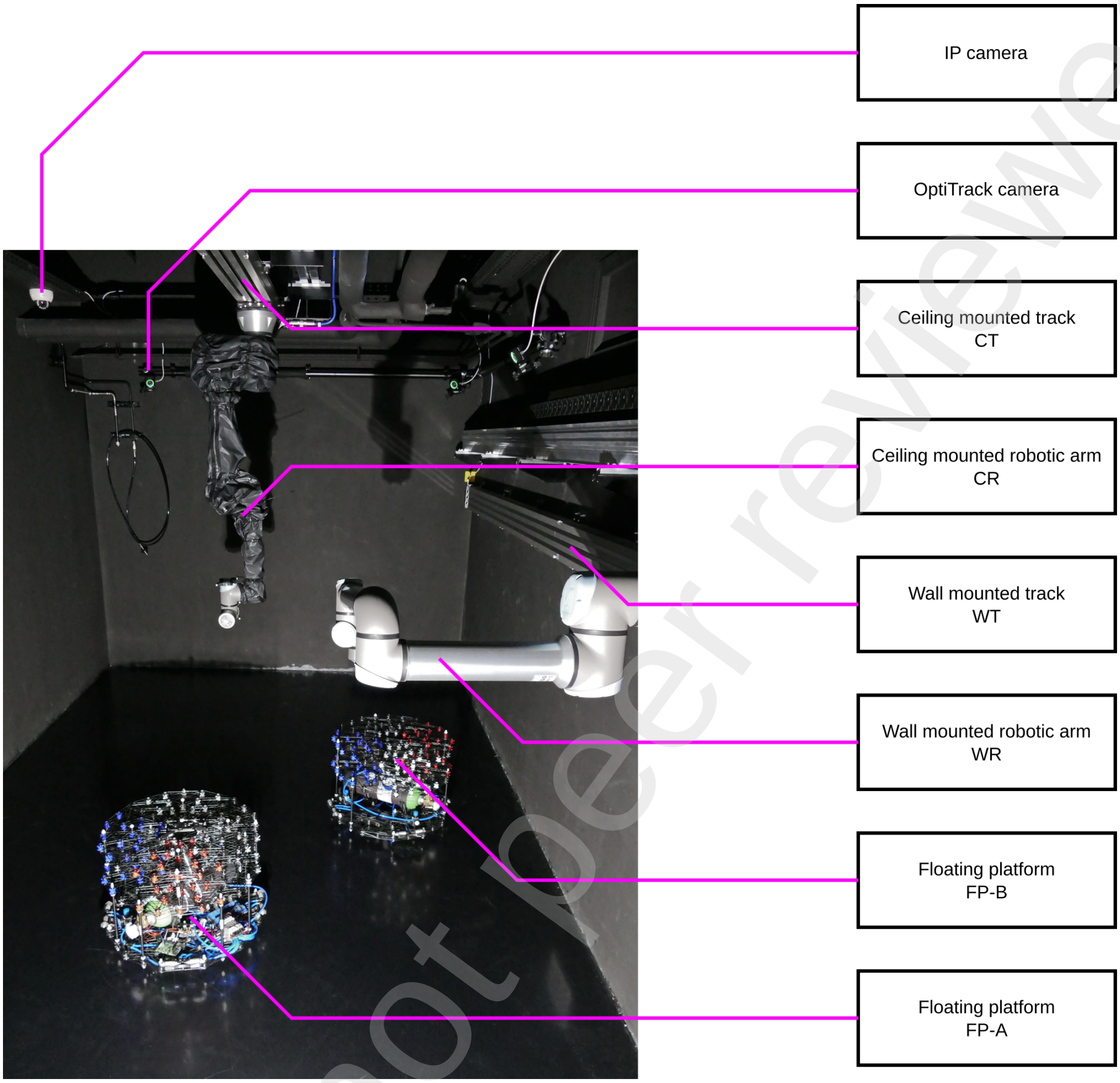

Figure 2: Actual Zero-G Lab.

Construction of the Zero-G Lab

The Zero-G Lab is located at the Interdisciplinary Centre for Security, Reliability, and Trust (SnT), University of Luxembourg, Kirchberg, Luxembourg. The overall facility comprises a room with overall dimensions of 6 meters in width, 7 meters in length, and 2.30 meters in height, housing an enclosed experimentation area. The experimentation room measures 3 meters in width, 5 meters in length, and 2.30 meters in height (W×L×H). Two small windows, each measuring 1 meter by 1 meter, are strategically located to enable observation of experiments. These windows can be covered with non-reflective black textile blinds from both the inside and outside when necessary. Furthermore, to authentically replicate the visual characteristics of orbital scenarios, the laboratory features a black-painted background to create a dark visual environment and minimize light reflection.

Evident in Fig. 2, this state-of-the-art facility also utilizes two sets of robotic arms mounted on robotic rails, two floating platforms (FP), a flat epoxy floor, and other sensory devices.

Epoxy Floor

The lab floor is meticulously designed, measuring 3 meters by 5 meters, and is coated with a flat black epoxy, ensuring a frictionless surface for the floating platforms. Its foundation consists of a precisely leveled concrete layer,

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aligning perfectly with gravity. The foundation is further complemented by three layers of epoxy, each approximately 0.6 to 0.7 centimeters thick. Prior to the application of each epoxy layer, a laser tracker was employed to meticulously inspect and rectify any irregularities, including the elimination of air bubbles. The construction process of the epoxy floor is documented in Fig. 3. This floor boasts an exceptional flatness tolerance of within 25 micrometers, as measured by a laser tracker device. It can support objects weighing up to 300 kilograms at any point without incurring damage. To maintain its optimal condition, the floor undergoes regular upkeep, including cleaning with microfiber mops and a solution composed of 30% Isopropyl alcohol and distilled water

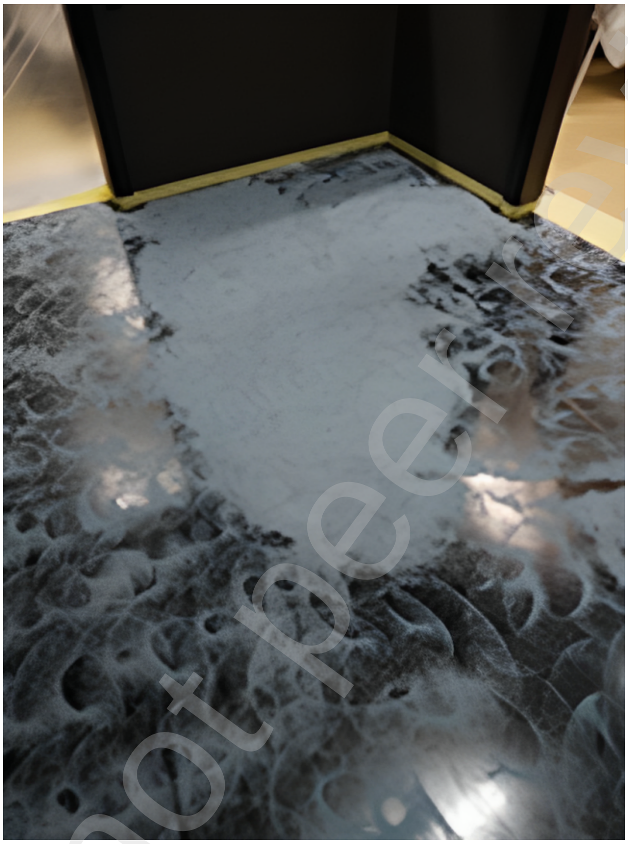

Figure 3: Epoxy floor's construction phase.

Floating Platform (FP)

The air-bearing floating platforms (FPs) within the Zero-G Lab are specialized devices that utilize high-pressure airflow to create a mechanical separation between the platform's nozzles, located beneath it, and the flat epoxy floor. This absence of mechanical contact allows for frictionless 2D motion, offering an ideal environment for simulating free-floating and free-flying motion in space. The FPs enable the installation of satellite and space debris mock-ups or active space-debris removal systems on top [7–11]. It can also be used as landing emulator [12, 13] or as sloshing test emulator of satellites' fuel-tanks [14]. The lab is equipped with two FPs, each featuring an additional eight horizontal nozzles to ensure comprehensive 3-DoFs movement. By activating these nozzles in specific configurations, the floating platforms can be driven along two translational axes, X and Y, and rotated around the Z-axis (yaw). It is important to consider that the endurance of the FPs depends on the frequency of nozzle actuation, with more frequent use resulting in reduced endurance. Besides, the addition of mass onto the floating platform decreases its operational time. Generally, for typical GNC applications, the endurance of the floating platform ranges from 30 to 40 minutes, depending on the propellant supply. These FPs are propelled by a high-pressure air supply, that is sourced either directly from a 30-liter compressed air station or through on-board 3-liter carbon-fiber compact air bottles, each pressurized to 300 bar. To ensure precise control and safety, the system incorporates multiple pressure regulators that reduce the effective pressure

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at the nozzles and air-bearings. Notably, the solenoid valves within the system are designed to withstand a maximum pressure of 10 bar, ensuring reliable and safe operation.

Rail enabled robots

Robotic Arms

The Zero-G Lab is equipped with two 6-degrees-of-freedom (DoF) UR10e robotic arms manufactured by Universal Robots, enabling precise emulation of the full 6D dynamic motion, encompassing 3 degrees of freedom in position and 3 in orientation. Such motions allow mimicking the movement of two space assets engaged in space operations. These robotic arms are mounted individually on separate robotic rails, one secured to the wall and the other to the ceiling. Significantly, these rails introduce an additional seventh degree-of-freedom to each robotic arm, enhancing their versatility for simulation purposes. Each arm boasts a working radius of 1300 mm and facilitates the attachment of various modular additions to the end-effector, including cameras, sensors, grippers, or mockup models. Moreover, the 6-DoF revolute joint arms come equipped with integrated force sensors at the flange, and there is an option to mount external force sensors as needed. Payloads of up to 10 kg may be attached to the robotic arms.

Rails

To expand the workspace for motion emulation, the lab employs motorized linear rails provided by Cobotracks. Each robotic arm is securely affixed to the mobile slider of these rails, allowing for extended reach. The ceiling-mounted and wall-mounted tracks offer a substantial stroke length of 3204 mm and 4330 mm, respectively, with a repeatability of 0.1 mm. Additionally, the base of the robots can traverse the rails at a maximum linear velocity of 500 mm/s.

Both the wall-mounted and ceiling-mounted robot systems are outfitted with individual Teach Pendant (TP) systems, providing an interface for controlling the robots, particularly for simpler applications.

Other equipment

- Motion Capture System (MCS)
  The Zero-G Lab is equipped with an array of eight Primex 13W cameras designed for the OptiTrack Motion Capture System. This MCS system operates at a rate of up to 240 Hz and utilizes invisible 850 nm infrared illumination. Each of these cameras has standard 3.5 mm lenses and 850 nm band-pass filters. These cameras are strategically positioned to cover every angle within the laboratory area, ensuring comprehensive tracking capabilities. The system's hardware and specialized tracker software enable submillimeter real-time localization. The primary tracking targets within the system are small reflective balls, known as markers. These markers can be either passive, lacking an electrical source, or active, with an incorporated power supply. As the MCS cameras track these markers, the 'Motive' software employs triangulation to calculate their precise positions once calibrated. To establish a local coordinate system with positional errors less than 0.30 mm and rotational errors less than 0.5 degrees, a minimum set of four markers must be attached to different surfaces of the test object.

- IP Cameras
  The lab is equipped with three 5-megapixel Reolink RLC-422 dome cameras, each featuring a 4x optical zoom capability. These IP cameras are employed for real-time viewing and recording of experiments. Leveraging the Reolink software, operators have the flexibility to pan and zoom the visuals as needed, ensuring comprehensive coverage and monitoring during experiments.

- Illumination
  To recreate orbital scenarios within the facility, the Zero-G Lab employs a Godox SL-60 Video Light [15, 16]. This LED light source has a 60-watt rating with dimensions of 23 cm × 24 cm × 14 cm. It emits light at a temperature of 5600 K, closely resembling the characteristics of daytime sunlight [17]. To simulate a range of illumination conditions encountered in space environments, two light source modifiers are available: a collimator and a reflector. Additionally, the lamp can be affixed to the robotic arms for dynamic illumination scenarios or placed statically on a tripod for stationary lighting setups.

- Gripper
  A Robotiq three-finger adaptive gripper, weighing approximately 2.3 kg, is employed for specialized operations within the lab. This gripper has the capability to securely grasp objects weighing up to 2.5 kg, applying a grip force within the range of 30-70 N [18].

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- Cubesat mock-ups
  The Zero-G Lab features experiment-specific Cubesat mock-ups, tailored to the research needs. Currently, the lab houses a 1U CubeSat model with realistic solar panels and a 3D-printed 0.6x scaled 6U Cubesat, designed for experimentation purposes. Additionally, mock-ups can be acquired or custom-manufactured as needed to suit specific research requirements.

Setup

All hardware equipment is seamlessly interconnected within the local laboratory network using either Ethernet cables or a WiFi network. Specifically, the robotic arms and rails are connected via Ethernet cables, while the Floating platforms access the network through a wireless LAN connection. Both the Motion Capture System (MCS) and IP cameras are integrated through the LAN network as well. To orchestrate the coordination of these hardware components and corresponding software, the Robot Operating System (ROS) network is employed as a middleware. This framework facilitates seamless communication and control of devices within the lab's network. In particular, for robot control, the Universal Robots ROS driver [19] is integrated as part of the Zero-G Lab's ROS control framework. Additionally, the robotic rails are managed using an in-house implementation of a ROS-control-based driver [20].

The intricate setup of the laboratory's robotic network is depicted in Fig. 4, providing a visual representation of the network architecture.

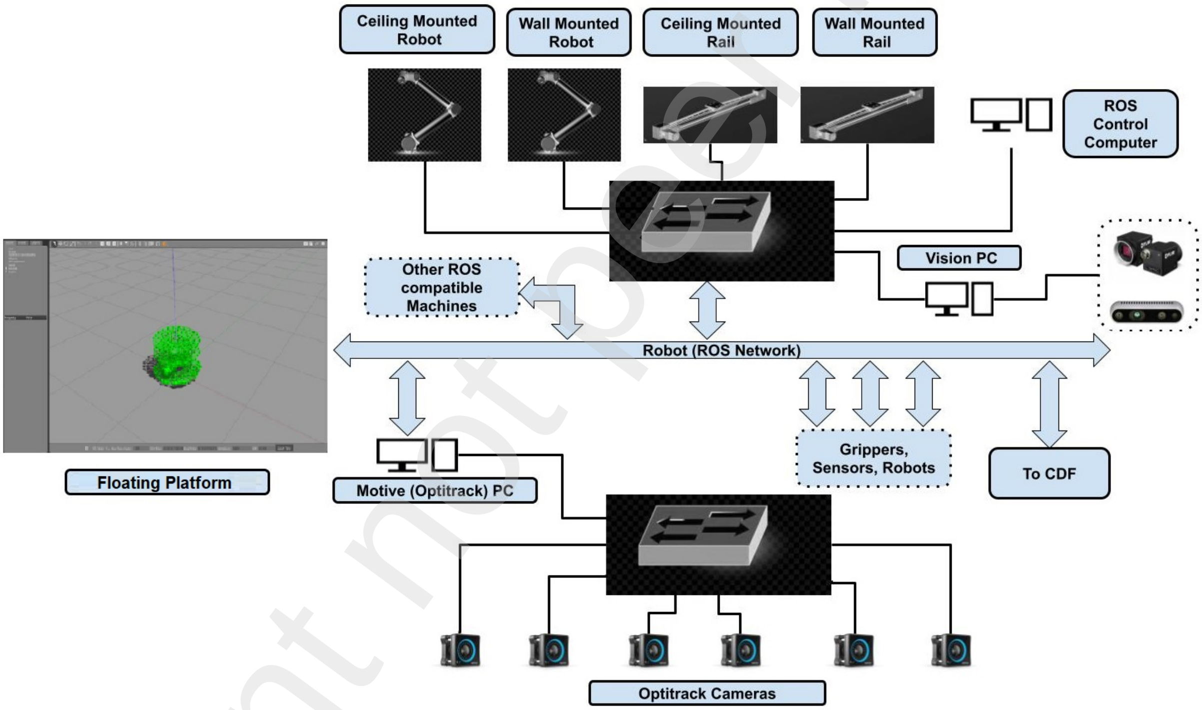

Figure 4: Setup of the robotic network.

The lab's control station comprises computers connected to hardware interfaces and the two teach pendants, offering a central command hub for managing experiments, and shown in Fig.5. External software and devices are seamlessly integrated with the workstation to access and configure any hardware equipment as needed during experiments. The control PC, depicted as the ROS Control computer, serves as the ROS master and runs nodes responsible for controlling the robots, rails and other hardware equipment. An in-house-developed wrapper facilitates the control of the rails over the laboratory network using ROS. This, combined with data from the robotic arms, provides comprehensive ground truth information, enabling synchronized control of the rails and arms using the wrapper. Additional ROS nodes, such as vision-based cameras, grippers or other sensors, are launched separately from another computer. Importantly, any ROS-compatible device, be it a PC, robot, or floating platform, can be easily connected to the network. Data from

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the MCS cameras, connected over a different network, become accessible in ROS through the use of appropriate commands.

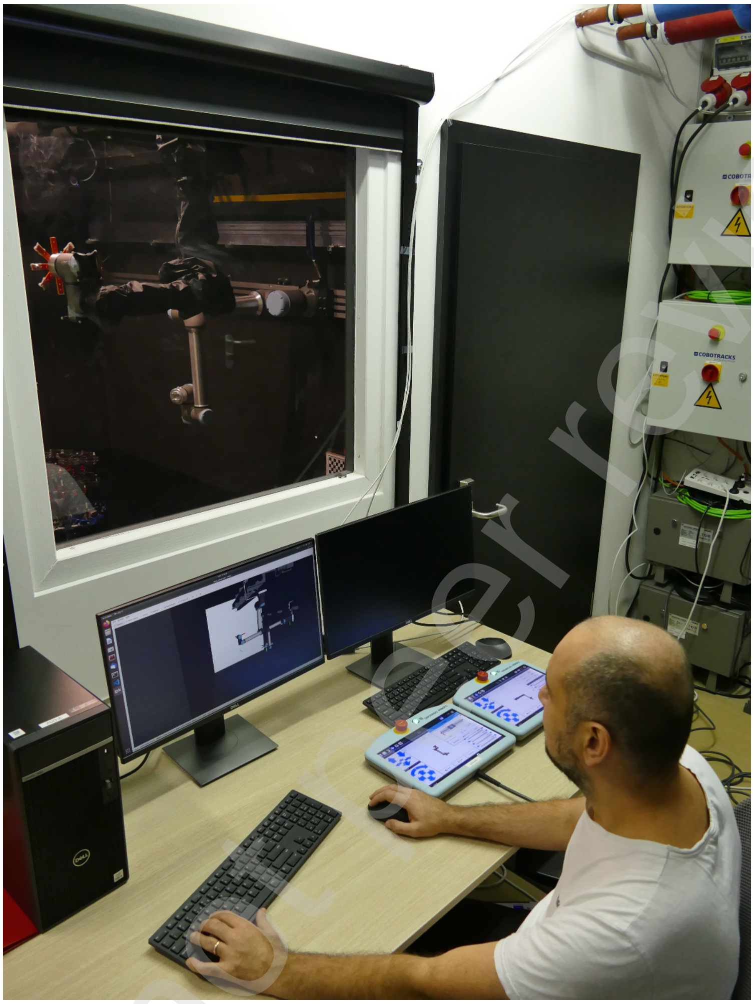

Figure 5: Control station PC of Zero-G Lab.

To visualize the entire robotic setup within the Zero-G Lab, the native ROS visualization environment, RViz, is utilized. This visualization tool offers a comprehensive view of the lab's robotic assets, as demonstrated in Fig. 6. RViz enables visualization of simulations before their execution on the physical hardware, crucial in ensuring the safety of operations. RViz also allows for real-time monitoring of actual motion during experimentation.

Experiments

Prior experiments conducted in the Zero-G Lab include GNC enabled rendezvous and proximity operations, cooperative docking, free-floating satellite motion, orbital interactions, image acquisition for computer vision, etc. [6, 15, 21–25].

Ethics statements

Not Applicable

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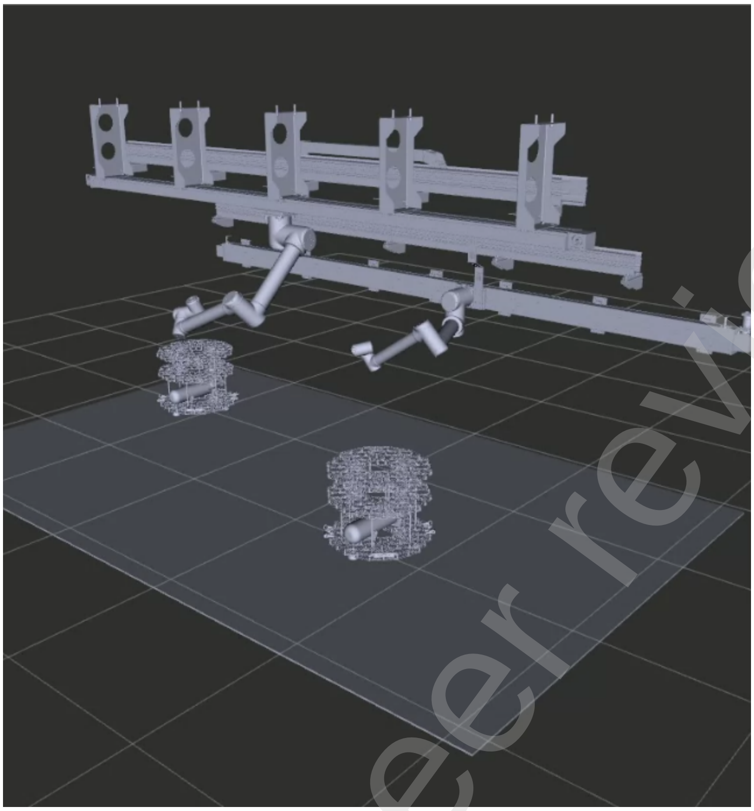

Figure 6: RViz interface of Zero-G Lab.

CRediT author statement

Miguel Olivares-Mendez: Conceptualization, Methodology, Investigation, Writing - Original draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Barış Can Yalçın**: Methodology, Software, Investigation, Writing - Original draft, Writing - Review & Editing. **Mohatashem Reyaz Makhdoomi**: Methodology, Software, Validation, Investigation, Data Curation. **Vivek Muralidharan**: Software, Investigation, Writing - Original draft, Writing - Review & Editing. **Zhanna Bokal**: Conceptualization, Methodology, Software, Investigation, Resources. **Miguel Ortiz Del Castillo**: Conceptualization, Methodology. **Vincent Gaudilliere**: Conceptualization, Methodology, Software, Validation, Investigation, Supervision. **Leo Pauly**: Methodology, Software, Validation, Investigation. **Olivia Borgue**: Conceptualization, Methodology, Investigation. **Mohammadamin Alandihallaj**: Methodology, Software. **Jan Thoemel**: Conceptualization, Methodology. **Ernest Skrzypczyk**: Software. **Arunkumar Rathinam**: Methodology, Software, Validation, Investigation. **Kuldeep Rambhai Barad**: Software, Investigation. **Abd El Rahman Shabayek**: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing, Supervision. **Andreas M. Hein**: Supervision, Project administration. **Djamila Aouada**: Conceptualization, Methodology, Investigation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Carol Martinez**: Conceptualization, Methodology, Software, Validation, Investigation, Writing - Review & Editing, Supervision.

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the national patent agency. The national patent application in Luxembourg named “Pneumatic floating systems for performing zero-gravity experiments” has been filed and it is still under evaluation process, the patent application file number is LU503146.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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