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Zero-G Lab: A multi-purpose facility for emulating space operations

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A B S T R A C T

During orbital rendezvous, the spacecraft typically approach in the same orbital plane, and the phase of the orbit eventually aligns. Potential rendezvous and docking missions need to be emulated and tested in an on-ground facility for micro-gravity research prior to meeting the harsh conditions of space environment. For orbital docking, the velocity profile of the two spacecraft must be matched. The chaser is placed in a slightly lower orbit than the target. Since all these tasks are quite complex and the realization of space missions are very expensive, any space-related hardware or software's performance must be tested in an on-ground facility providing zero gravity emulation before initiating its operation in space. This facility shall enable emulation conditions to mimic pseudo zero gravity. It is of critical importance to be equipped with all the necessary "instruments and infrastructure" to test contact dynamics, guidance, navigation and control using robotic manipulators and/or floating platforms. The Zero-G Laboratory at the University of Luxembourg has been designed and built to emulate scenarios such as rendezvous, docking, capture and other interaction scenarios between separate spacecraft. It is equipped with relevant infrastructure including nearly space-representative lightning conditions, motion capture system, epoxy floor, mounted rails with robots, capability to integrate on-board computers and mount large mock-ups. These capabilities allow researchers to perform a wide variety of experiments for unique orbital scenarios. It gives a possibility to perform hybrid emulations with robots with integrated hardware adding pre-modeled software components. The entire facility can be commanded and operated in real-time and ensures the true nature of contact dynamics in space. The Zero-G Lab also brings great opportunities for companies/startups in the space industry to test their products before launching the space missions. The article provides a compilation of best practices, know-how and recommendations learned while constructing the facility. It is addressed to the research community to act as a guideline to construct a similar facility.

1. Introduction

In recent years we have been witnessing an emerging generation of companies focusing on developing business in Low Earth Orbit (LEO). The use of CubeSats, nano and small satellites has initiated a democratization of the satellite business. These types of

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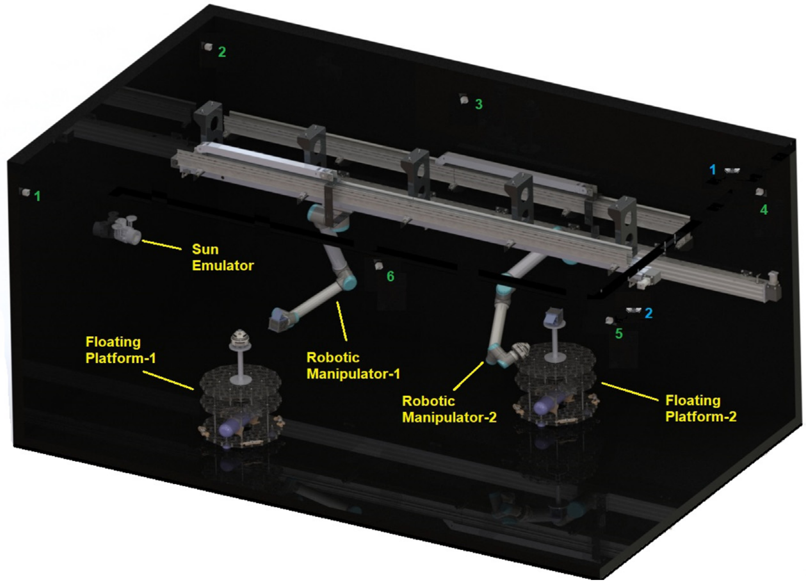

Fig. 1. Zero-G Lab's CAD model render.

satellites are now used by companies to develop in-orbit servicing solutions such as Earth observation, on-demand satellite communication, 5G connection or surveillance. These tasks focus on the use of a single satellite or large constellations. As in the traditional satellite companies, these approaches completely rely on their system verification and validation and other flight preparations on simulations, using dynamics modeling. Orbital emulation facilities have been used to test spacecraft attitude dynamics with open-loop or closed-loop approaches (involving sensors, actuators, board computers) in order to verify and validate functions and performances. In the past, most of the emulations and tests of micro-gravity operations were performed in the area of Guidance, Navigation and Control (GNC) system development, using 3-axis motion facilities, mainly to support verification of relative motion of spacecraft with respect to inertial space. As part of the democratization of in-orbit activities, in the latest years, many companies are focusing on business models that provide services to other satellites such as re-orbiting, re-fueling, maintenance or repairing, space debris removal [1]. Contrary to the formerly mentioned tasks, these operations demand close cooperation between two or more satellites and, therefore, demand a precise GNC approach to perform the approaching, close contact, docking and rendezvous. The close operations are critical and require to be tested on-ground before the launch to perform a proper Verification & Validation (V&V) of the GNC and the Space Situational Awareness (SSA) algorithms in conditions that are similar to micro-gravity. Therefore, the simulators are not sufficient to prepare these complex GNC and SSA approaches and hence more advanced V&V emulation systems are necessary.

This paper presents the construction steps to setup the Zero-G Lab, which is a multipurpose facility, to emulate a large variety of in-orbit operations in different orbital scenarios utilizing different system components such as perception, control, robotic interaction and path planning [2–6]. The rendering of the visual CAD model representation of Zero-G Lab is shown in Fig. 1, green numbering represents the OptiTrack Motion Capture System (MCS) cameras, whereas blue numbering shows IP cameras. Zero-G Lab has an internal control station PC as given in Fig. 2. This paper can be used as a handy guide to construct, operate and/or improve similar facilities in other research institutions, universities and companies. The potential proximity emulations that can be realized in Zero-G Lab are listed in Table 1.

Fig. 2. Control station PC of Zero-G Lab.

Table 1
Potential proximity emulations.

	Contact	Non-contact
Cooperative	Rendezvous for; Maintenance/repair, Human transfer, Re-fuelling, Structure assembly, Re-orbiting	Preparation to berthing, Formation flight
Non-cooperative	Interception	Inspection, Blinding

The outline of this paper is as follows: Section 2 visits the existing facilities around the world to emulate in-orbit operations and scenarios. Section 3 presents the construction of the Zero-G Lab and Section 4 covers its setup to enable different emulation scenarios. Section 5 shows how to use the Zero-G Lab and its capabilities. Finally, Section 6 concludes and discusses possible future works to improve this facility and emulate more orbital scenarios.

2. Other facilities

There are various facilities around the world implementing different technologies and strategies for on-ground emulation of in-orbit operations for different orbital scenarios, that represent micro-gravity at different degrees of freedom (DoF). Some facilities [7–10] use robotic arms mounted in robotic rails to generate 6-DoFs, without emulating orbital mechanics in micro-gravity. Others are based on pneumatic floating platforms equipped with air-bearings and nozzles over a flat surface (granite table or flat-floor) to emulate micro-gravity in at least 3-DoFs [11,12]. There are also different facilities that combine 6-DoFs robotic arms and rails with 3-DoFs floating platforms [13]. Summarized descriptions of the above-mentioned facilities to emulate in-orbit operations and scenarios are given below.

2.1. ASTROS, Georgia Institute of Technology (Georgia Tech Lab), USA

The experimental facility of Georgia Institute of Technology ASTROS [12] allows for realistic testing of spacecraft Autonomous Rendezvous and Docking (ARD) maneuvers with 5-DoFs. Its main objective is to test vision-based spacecraft pose estimation, navigation and guidance algorithms. The facility has a test area that consists of a 4 $m \times 4$ m flat epoxy floor and a control room to monitor and command the experiment execution. The test area consists of lower and upper stages.

In the lower stage, a high-pressure experimental air-bearing floating platform hovers on the floors to emulate friction-less operations. Two types of air-bearings are used for the friction-less operation of the 5-DoFs Spacecraft Simulator ARD facility: three linear air-bearing pads and a hemi-spherical air-bearing cup. The linear air-bearding pads make it possible to achieve almost friction-free translation motion of the entire system over a flat epoxy floor, while the hemi-spherical air-bearing cup is utilized to enable friction-free rotational motion of a spacecraft bus. External high-pressure tanks provide the floating platforms with high pressure (3295 *psi*) air for their operation, enabling them to carry a maximum weight of 175 lbf for the air-bearing pads and 400 lbf for the air-bearing cup. All floating platforms can be remotely controlled through an on-board computer, and manually operated with external switches.

In the upper stage, a typical spacecraft bus is emulated with a brass structure supported on the hemi-spherical air-bearing cup that enables the rotation on the upper stage with 3-DoFs. The upper stage has twelve 5 N thrusters, in clusters of three, operated with cold-nitrogen gas or compressed air.

A projector installed on the ceiling is used to project images from Earth orbit against a projection screen on one of the walls. In addition, dedicated lights mimic space-like lighting conditions in the visible spectrum. The vision-based ARD activities are enabled through on-board and ceiling-mounted cameras, complemented with laser scanners. Moreover, construction imperfections in the epoxy floor flatness are studied, modelled and compensated during experiments. This facility provides an overview of real-time simulation/visualization environments, developed in MATLAB/VRML (Virtual Reality Modeling Language) enabling rapid prototyping, validation and testing of ARD control algorithms. Accurate and drift-free algorithm calibrate attitude measurements using a single camera and a cross-shaped laser module.

2.2. ORBIT and GRALS, ESA-ESTEC, Netherlands

The ORBIT facility at the European Space Agency (ESA) [11] is a 45 m^2 air bearing facility located at European Space Research and Technology Centre (ESTEC), specifically targeted at orbital robotics. The facility consists of a 5 $m \times 9$ m flat epoxy floor. A set of fourteen VICON motion tracking cameras enables position tracking of moving objects on the floor. The epoxy floor is complemented with a pressurised air installation that provides a filtered pressure and flow regulated air outlet. Air bearing platforms are used to provide free floating capability for the test objects. Three rows of 45 *mm* Bosch-Rexroth aluminium profiles are mounted horizontally to the walls surrounding the floor. In these profiles additional hardware (such as planetary terrain mock-ups, or cameras) is mounted. The facility is meant to be large enough to cope with large payload structures to be operated during an extended amount of time, such as those typical for spacecraft interaction scenarios. In addition, as part of ESA's Orbital Robotics and GNC Laboratory, ESTEC has a GNC Rendezvous and Landing Simulator (GRALS) [9]. The GRALS is a small robot arm mounted on a 33 m long rail, long enough to span the length of the Orbital Robotics and the GNC Laboratory, and able to interact with the ORBIT facility to combine robotics and GNC operations. Moreover, it is possible to install various equipment in the GRALS, such as range sensors, cameras to test vision-based software, and a gripper to seek and grab a target object. This facility enables research and development activities within ESA, and rapid prototyping of GNC systems for ESA's missions.

2.3. ADAMUS, University of Florida, USA

The ADvanced Autonomous MUltiple Spacecraft laboratory (ADAMUS) is a 6-DoFs spacecraft simulator testbed placed on a 3.96 $m \times 4.57$ m flat epoxy floor. Air bearing technology allows a moving platform to move torque and force free as it would in space. The objective of ADAMUS is to perform hardware-in-the-loop (HIL) experiments for spacecraft GNC, as well as proximity contact maneuvers such as on-orbit assembly, or servicing. The testbed is composed of a Translational Stage (TS) operating as a moving platform, with an Attitude Stage (AS) on top. Position and attitude data are provided by an external arrangement of cameras and sensors. The TS provides 3-DoFs, two of them provided with air-bearings hovering on the epoxy floor and the third, which is the vertical translational DoF, is provided through a Counterbalancing System (CS) hanging from the TS. The TS also carries the pressurized air tanks necessary for the air bearings. The AS represents a spacecraft, containing the GNC testing subsystems and providing the three rotational DoF in ADAMUS. 3-DoFs are enabled through a spherical air bearing, that doubles as a connective joint with the TS. The CS, enabling the vertical degree of freedom, consists of a counterbalancing deck with the same mass as the AS and its supporting column to maintain the zero gravity effect. The 6-DoFs are controlled with twelve thrusters, without the implementation of emulated dynamics and servo actuators, providing a more realistic emulation than other facilities through the vertical translational DoF. The thrusters are powered by two lithium-ion batteries connected to an on-board power management system. ADAMUS testbed is designed for testing nano-satellites, however it is flexible; by substituting the attitude stage, different categories of spacecraft below 10 *kg* can be evaluated. In addition, a balancing platform allows the MP to modify the position of its center of mass [13,14].

2.4. TRON, EPOS and TEAMS, Germany

In Bremen, the German Aeronautics Centre (DLR) has developed the testbed for Robotic Optical Navigation (TRON) [10]. This HIL (Hardware-in-the-loop) facility is meant to support the development of optical navigation technology through the implementation of a robotic arm mounted on a 10 *m* long linear track, used for simulating descent and landing scenarios. Different landing terrains can be customized and emulated on the different walls of the testbed, where laser based metrological equipment is used for high precision ground measurements. An illumination system illuminates the landing terrains, enabling descent and landing scenarios from 100 *km* altitude to touchdown, and a laser tracking system for ground-truth measurement. TRON can also be used for breadboard qualification up to Technology Readiness Level (TRL) 4, and flight model qualification up to TRL 6. The DLR has also developed the European Proximity Operations Simulator (EPOS) test facility in Oberpfaffenhofen, Germany, to study rendezvous and docking scenarios. This testbed consists of two robot arms and background illumination systems to mimic rendezvous scenarios, either for collaborative rendezvous or for Active Debris Removal (ADR). The predecessor of the current rendezvous facility, EPOS 1.0, was a joint test facility developed by DLR and ESA for emulation of approach maneuvers during the final meters of the rendezvous phase prior to docking. One of the latest test campaigns was the test and verification of the rendezvous sensors of the European Automated Transfer Vehicle (ATV). The EPOS 1.0 was improved to the EPOS 2.0, a new rendezvous and docking test facility which provides the capabilities for complete rendezvous processes with special focus on-orbit servicing and spacecraft de-orbit missions [8]. The DLR has also a Test Environment for Applications of Multiple Spacecraft (TEAMS). The objective of TEAMS is to emulate the forces and torque free dynamics of satellites. With a flat-surface arrangement consisting of two 4 $m \times 2.5$ m granite flat plates where air-bearing platforms can hover. TEAMS can be utilized to study formation flight using different “vehicles” to attain 3 or 5-DoFs. The vehicles are made of a lower translation platform with 2-DoFs, connected to an upper attitude platform (3-DoFs) through a spherical air bearing. The pressurized air for the translation platform and spherical air bearing is provided through tanks mounted on the translation platform [15].

2.5. Platform-art, GMV, Spain

In Madrid, Spain, GMV has developed the platform-art dynamic test facility, a testbed for the validation of space GNC technologies and metrological equipment, equipped with an air-to-air metrological dynamic stimulation, through the recreation of trajectory attitude profiles using a robotic arm [7,16]. The testbed consists of two robotic arms mounted on a 16 *m* rail, smaller robotic arms for mock-up support, a laser based metrological equipment with μm accuracy, an illumination system, sensors to be used in open and closed loop, and the possibility to include Lunar surface mock ups. Application cases include collaborative and non-collaborative rendezvous, operations in small-body missions and descent and landing scenarios.

2.6. Spacecraft dynamics simulator facility, Caltech Aerospace Robotics and Control Lab, California, USA

The Aerospace Robotics and Control Lab at Caltech has developed the Spacecraft Dynamics Simulator facility [17]. This facility has one of the largest university owned flat floors where three Multi-Spacecraft testbed for Autonomy Research (M-STAR) platforms are used. M-STAR platforms are modular 3 to 6-DoFs spacecraft simulator hardware used to study trajectory attitude profiles, formation flight and emulate spacecraft GNC processes, among others. The M-STARs are composed of a lower translation module with 2-DoFs flat air-bearings for hovering over the flat epoxy floor and are connected to an upper module through a spherical air-bearing, with 3-DoFs. One more DoF is provided in the vertical direction with flight-like actuators. M-STARs modularity enables the operation of the platform with 3-DoFs, 4-DoFs, 5-DoFs, and 6-DoFs with minimal mechanical modifications. Attitude control is achieved with sixteen air-filled non-latching solenoid valves that act as thrusters, and four reaction wheels. The facility has an air filling station for filling the air tanks on-board of the M-STAR platforms that supply air to the flat air bearings, spherical air bearing, and sixteen on-off thrusters. M-STAR includes all the necessary on-board sensors, actuator systems and computing capabilities to achieve full DoF control. The pose of the spacecraft simulator is estimated using fourteen VICON MCS cameras mounted on the ceiling.

2.7. AUDASS, US Naval Postgraduate School, US

The Satellite Servicing Laboratory, part of the Astro-Engineering Laboratory at the US Naval Postgraduate School has developed the Autonomous Docking and Spacecraft Servicing Simulator (AUDASS). AUDASS has two independent floating platforms intended to be used as chaser and target to carry out testing of satellite servicing and proximity formation flight activities. The 0.76 *m* in diameter floating platforms hover over a friction-less 1.8 $m \times 2.4$ $m \times$ 0.27 *m* granite table via air-bearings, capable of two translational and one rotational DoF. The platforms contain air thrusters with air or nitrogen supply tanks and a momentum wheels for angular control. In addition, the base body carries an attitude sensor, an angular rate sensor and manipulators [18]. A previous version of this facility implemented one floating platform over the granite table, complemented with two robotic arms with which it emulated GNC processes [19].

2.8. Carleton University, Canada

At Carleton University in Ottawa, the Spacecraft Robotics and Control Laboratory has a 3.6 m $\times$ 2.4 m granite table for emulating space dynamics using compressed air-based floating platforms. This precision table is used by graduate students and researchers training for validating GNC systems of spacecraft proximity operations, inspection maneuvers and robotic capture [20].

2.9. Fokker space & systems, Netherlands

At Fokker Space & Systems in the Netherlands, a 4 $m \times 7$ m epoxy flat-floor facility has been constructed for performing the functional testing of the European Robotic Arm (ERA). The facility has a flatness of 2μm per *m*. The ERA is an external 10 *m* long manipulator intended for assembly maintenance and servicing. The flat-floor facility is used to validate the ERA software simulator. In this facility, the robotic arm is supported by a servo-controlled free-moving support vehicle containing air-bearing subsystems, and a system for tracking the arm support. This configuration has several advantages, such as the dynamics of the ERA not being modified by the inertia properties of support systems, and the fact that the vehicle adjusts itself to compensate for floor unevenness. A flat surface reference is established by a plane of laser light [21].

2.10. ORION, Florida Institute of Technology, USA

The Orbital Robotic Interaction, On-orbit servicing, and Navigation (ORION) laboratory is a closed-loop floating platform facility developed by the Florida Institute of Technology with a 9.4 $m \times 9.6$ m epoxy surface. The ORION laboratory has the objective of testing spacecraft GNC systems for formation flight, proximity maneuvers and autonomous capture. It features 6-DoFs air-bearing floating platforms capable of moving an 80 kg payload with a maximum acceleration of 1 m/s^2 up to a speed of 0.25 ms^{-1} along its axes [22]. The battery-powered platforms are equipped with eight thrusters, a reaction wheel, capture devices and wireless communication systems. Every floating platform is tracked with an optical tracking system that implements twelve cameras OptiTrack Prime 17 W.

2.11. NASA, USA

NASA has a history of developing facilities to emulate in-orbit operations and scenarios such as the Air Bearing Floor (ABF) at NASA Johnson Space Center [23], the Flight Robotics Laboratory at NASA Marshall Space Flight Center [24], and the Formation Control testbed at JFP [25]. The Johnson Space Center air-bearing floor is a 70 $m \times 98$ m epoxy floor with an average deviation of 6.5 μm. Test articles can be mounted on floating platforms suspended over the floor by air between them and the floor. The formation control testbed, also known as the Robodome at JFP, consists of a 12 m diameter circular room with a glass floor. There are three 6-DoFs autonomous floating platforms to demonstrate precision formation flight and to develop and test GNC algorithms and technologies. The floating platforms have a two translational DoF lower assembly and an upper assembly, connected by a spherical air-bearing (three rotational DoF), a third (vertical translation) DoF is provided by a vertical feet between the lower air bearing feet and the spherical air bearing. The lower assembly floats on three air-bearings supplied with pressurized gas (50 psi) from eight 4500 psi on-board air tanks, the air tanks supply the spherical air-bearing as well. Each of the three air-bearings is equipped with sixteen pairs of air jets.

2.12. Space Research Center, Polish Academy of Science (PAS), Poland

The Space Research Center at the Polish Academy of Science (PAS) has developed an air-bearing micro-gravity testbed to emulate control operations for free-floating satellite-manipulator systems in space. The PAS's testbed is composed of a 2 $m \times 3$ m flat granite table on top of which a 1.22 m long 2-DoFs robotic arm (6 kg) is mounted on a 12.9 kg base that is free to move and rotate in one plane utilizing three air bearings forming a three-point stance. The main difference between this and other micro-gravity emulation facilities is the robotic arm mounted on a floating platform with an on-board computer and arm joint-controller board. The whole arm-base assembly is a 18.9 kg aluminum structure where the weight of the arm is nearly half of the base weight, for this reason each of the two portions of the robotic arm must be supported on an air bearing platform. The air-bearings generate a thin film of air on which they slide, the air is pressurized and supplied from air tanks on top of the base [26].

3. Construction of the Zero-G Lab

3.1. Facility overview

The Zero-G Lab is constructed at the Interdisciplinary Centre for Security, Reliability and Trust (SnT), in the University of Luxembourg, Kirchberg, Luxembourg. This facility relies on a combination of robotic arms mounted on robotic rails, a super-flat epoxy-floor and floating platforms. It has been established to emulate on-orbit scenarios from GNC perspective, such as spacecraft proximity maneuvers, rendezvous, on-orbit maintenance and operations. In addition, since the laboratory emulates the visual appearance of orbital scenarios, it can be used to generate datasets to train perception algorithms and to test and validate perception and close control-loop approaches.

The facility consists of a room with a volume of 7 $m \times 6$ $m \times$ 2.30 m with a closed room inside for the experiments. The experiments room consists of 5 $m \times 3$ $m \times 2.3$ m (WxLxH) fully painted with non-reflective black paint. The room has two small windows of 1 $m \times 1$ m to monitor the experiments that could be covered with a blind made of non-reflective black textile from inside and outside. For remote monitoring of the experiments the facility is surveilled with three IP cameras connected to the laboratory network.

The Zero-G Lab is equipped with different robotic systems to emulate different types of orbital scenarios. There are two robotic arms of 6-DoFs to emulate the 6D dynamic motion of two space assets on space operations. Both robotic arms are mounted on separate robotic rails. One robotic rail is mounted on the wall and the other on the ceiling. The rails provide a seventh degree of freedom to each robotic arm.

To emulate orbital mechanisms and dynamics, Zero-G Lab floor is furnished with 3 $m \times 5$ m flat black epoxy. This floor has been installed in a micron-scale precision manner to have a specific smoothness along the full surface as shown in Fig. 6. We have designed and constructed two identical robotic pneumatic systems that can float over this floor. They are called floating platforms. Each floating platform is equipped with an air-pressured system that ejects air through three air-bearing under the platform to generate a air-cushion between the platform and flat-floor surface to generate friction-less interaction and emulate free-floating in-space dynamics. In addition, the floating platforms are equipped with eight nozzles to emulate the spacecraft propulsion system. A compressed-air filling and storage station has been designed and installed out of the experiments room to provide constant compressed-air supply and to fill smaller bottles for the floating platforms.

For the V&V of different GNC approaches the laboratory is equipped with a motion capture system. This system allows to estimate the pose of any robotic system or object in the room with under-millimetre precision at the frequency of 240 Hz. In addition, to visually recreate the illumination condition in-space the Zero-G Lab counts with a lamp that can be mounted on a static rail on the wall or in one of the robotic arms.

Any object, such as a satellite mock-up, can be installed on top of the floating platform or attached to the end-effector of the robotic manipulator. For the sake of clarity, frontal and lateral views are given in Fig. 3. Zero-G Lab in partial darkness with specific lighting conditions can be seen in Fig. 4. Robotic Manipulator-1's surface has black cover to block any possible lighting reflection, whereas Robotic Manipulator-2's has no cover to emphasize the difference in the photo. The orange 3D-printed object is attached to the end-effector of Robotic Manipulator-1 to highlight the importance of the lighting condition on reflective objects.

3.2. Robotic arms

The Zero-G Lab facility is equipped with two Universal Robots UR10e robotic arms. These 6-DoFs revolute joint arms come with an integrated force sensor at the flange. There is also a possibility to mount external force sensors if needed. Each arm is mounted on a rail that provides an additional linear motion. Each arm has a working radius of 1300 mm and different end-effector (like cameras, sensors, grippers or mockup models) can be attached to them. In the existing setup, the robots can be controlled over ROS network, where they can communicate and function with any other device. Apart from that, Teach Pendant (TP) system can also be

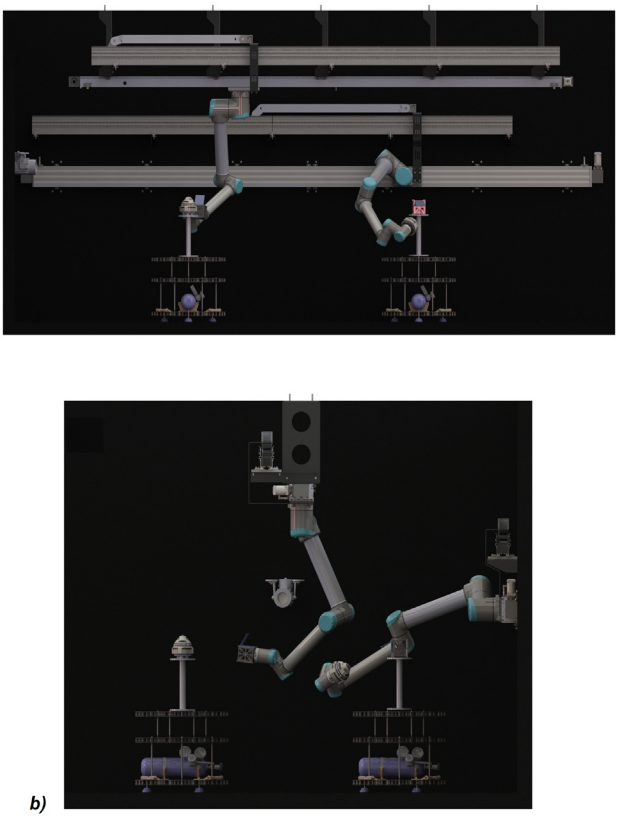

Fig. 3. a) Front and b) side views of CAD model render.

used to control the robots for simpler applications. The robots expose a motion based control interface (position and velocity) and can be fed position and velocity based waypoints.

3.3. Robotic rails

To extend the workspace of the robotic arms for spacecraft motion emulation, motorized linear rails have been utilized. The base of each robotic arm is mounted onto the moving slider of the rail. The ceiling mounted and wall mounted tracks have a stroke length of 3204 mm and 4330 mm respectively with a repeatability of 0.1 mm. Emulation with true-size mockups is possible up to a distance equal to the rail stroke-length. For some applications (e.g. test of camera based rendezvous) also larger distances with downscaled mock-ups can be realized. Each rail is capable of reaching a maximum linear velocity of 500 mm/s. A wrapper to control the rails over the laboratory network using ROS was developed inhouse and together with information from the robotic arms provides complete ground truth information. Therefore, the rails and arms can be controlled in a synchronized way using the wrapper. For simpler motions, the rails can also be controlled via the TP of the robotic arms using a custom URCaps plugin.

3.4. Epoxy floor

One of the major components of Zero-G Lab is its flat-floor facility constructed using black epoxy. The floor consists of three layers, which took one day per layer for installation in addition to the time for calibration. As the foundation has been installed, a concrete layer with the height adjusted to be perfectly leveled with respect to gravity. Construction phase of the first layer can be seen in Fig. 5. Then the 2nd and 3rd layers of epoxy were adjusted using sandpaper. Each layer is approximately 0.6 *cm* - 0.7 *cm* to build up the surface. After each step of the floor installation, as well as at commissioning, the whole surface has been examined. Each layer has been verified with a laser tracker and all inaccuracies, including bubble crates, have been detected and eliminated before the next layer of material is applied. The micronscale defects measured by the laser tracker device are given in Fig. 6.

3.4.1. Floor parameters consideration

For a proper operation and emulation of orbital dynamics, the floor prepared to be parallel to the air bearings' surface. In order to provide an optimal situation, the floor shall be compatible with the selected air bearings and compressed-air pressure. Follows a set of validated Key Performance Indicators (KPIs) to ensure the epoxy floor installation requirements:

- **Size:** The size of the epoxy floor is roughly 5 $m \times 3$ m over which floating platforms can hover without any friction. The importance of the size arises from spacecraft interaction requirements in scenarios like ADR. The tested objects need to have sufficient space to emulate the synchronization and freedrifting phases. Similarly, large payload structures require a large operational space. Maximum allowed object weight to be positioned at any point of the floor without causing any damage is up to 300 *kg*.
- **Precision/Flatness:** A high precision floor is considered with flatness within 25μm for frictionless translation of the spacecraft dynamics simulator using three flat air bearings. A defected flat floor leads to drift of the test objects due to gravitational force. Hence, general and local inclinations on the floor needed to be minimized. On a microscopic scale, the surface finish of the floor had to provide the necessary smoothness to allow the use of air bearing pucks. In order to verify the compliance of the floor to requirements, an examination of the floor flatness has been done using laser tracker, which also can be used to measure deviations along the gravity vector to fractions of a millimeter. In reality, however, no matter how the surface is measured, what really matters is how robotic spacecraft simulator floats on the epoxy floor. An ideal surface provides for little to no drifting of the float unit at any location on the test surface. The float unit shall sit perfectly still when it is floating above a flat surface on a cushion of air in a state of weightlessness.
- **Surface roughness:** The air bearings used by the platform operate with air-gaps of just a few tens of microns (approximately around 5 μm). A roughness tester has been used to measure the roughness values to make sure that the floor complies to all measured points. Discrepancy, from one end of the flat floor to the other, should take out a max of 2 *cm*.

3.4.2. Maintenance of the epoxy floor

In order to have a proper performance of the floating platform, it is convenient to follow some important procedures when entering and using the epoxy floor:

- **Surface smoothness:** It is important to maintain the surface smooth. Scratches can occur from any particle, such as dust *etc*, that become lodged in a vehicle's air bearings and subsequently leave microscopic marks on the floor. First of all it is planned to use sticky pads at all entrances to remove large particles from a person's feet and all personnel will be required to wear cleanroom shoe covers inside the test area. Also special clean-room shoes will be provided for walking on floor itself to distribute weight. Test area should be kept under slight positive pressure from ventilation. Filters should be installed on all outlet vents to mitigate outside dust.
- **Cleanliness:** To clean the floor, microfiber mops and a solution of 30% Isopropyl alcohol and distilled water will be

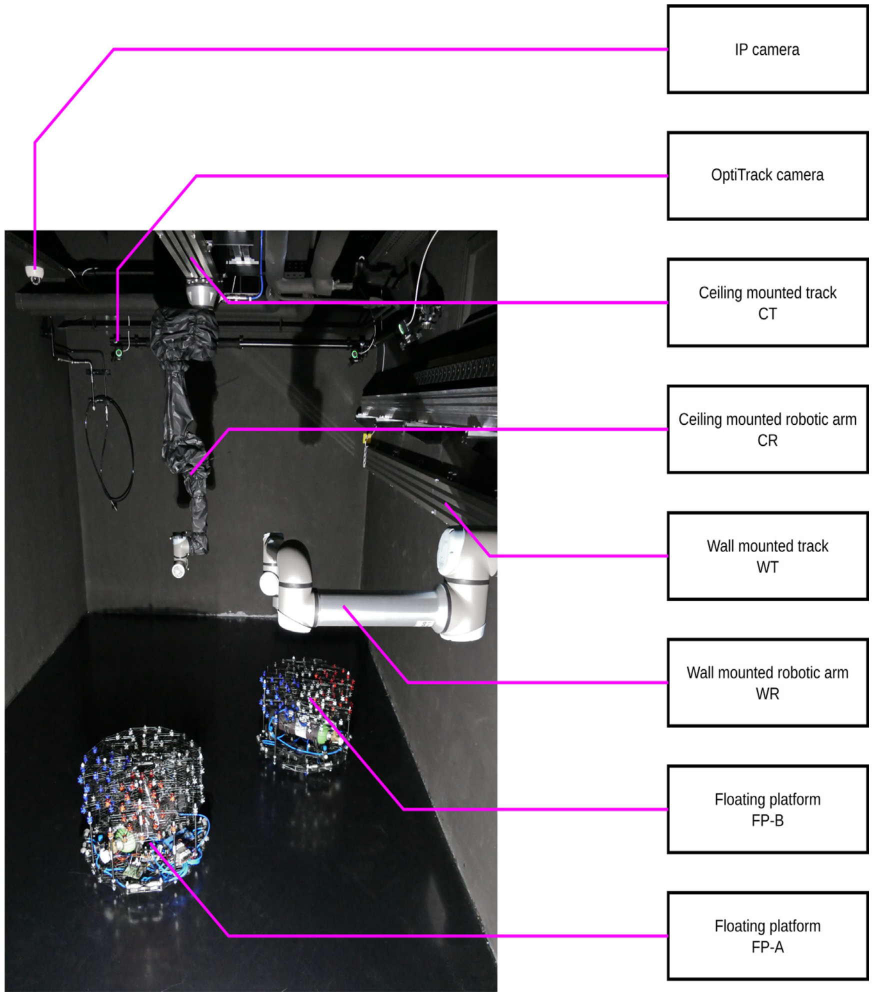

Fig. 4. Zero-G Lab in darkness.

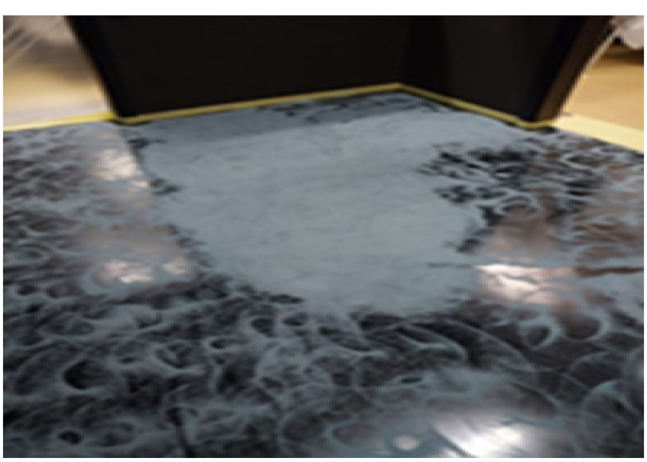

Fig. 5. Epoxy floor's construction phase.

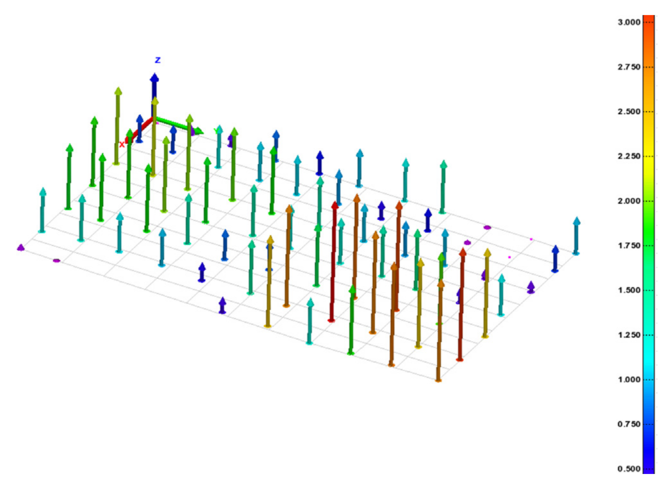

Fig. 6. Micron-scale defects on epoxy floor of Zero-G Lab.

used. The solution is constantly purified by pumping through a two-stage micronic filter. The cleanliness of the floor is qualitatively measured by laser sensors. In order to prevent damage of the floor surface, it shall be protected during periods of non-use; *e.g.* with a heavy rug or hardboard plates.

3.5. Compressed air filling station

In order to maintain the floating platform to function with consistency and dependability, it is crucial to assure an equal flow of air to each of the air bearings. The floating platform is designed to use the small pressurized air tube which is mounted on the platform and it has 200 *bar* pressure. There are two approaches to supply the floating platforms with air:

3.5.1. Using air pressure

The first approach is to charge 200 *bar* small platform tube via 300 *bar* bar pressure supplied by pressurized tubes. This can be done thanks to the installed compressed air filling station with two 300 *bar* 50 *l* big pressurized tubes. This is sufficient to recharge the small pressurized tube more than ten times. The overall time for charge is approximately 10 - 15 *min*. It is estimated that the tubes can be changed once in two weeks. There are two big 300 *bar* pressurized tubes connected in cascade, and it is supposed to keep two others as backups. A more detailed description of the compressed air filling station is below. The second approach is to directly actuate the air-bearings and nozzles by a single pipe, coming from the big pressurized air tube connection. In this case, the connection between the small pressurized air tube and air bearing-nozzle system is cut. Instead, it is directly connected to the single pipe from big pressurized air tubes. All the actuation is being realized by the big pressurized air tube couple. The pressure needed for air-bearings and nozzles is 5 *bar* - 6 *bar*. This pressure can be regulated by the pressure regulators located on the floating platform for both air-bearings and nozzles separately. If we need to actuate a max of four nozzles at the same time, one nozzle needs 120 *NLPM*, so it is 480 *NLPM*. One air bearing consumes 0.74 *NLPM*, so three air bearings consume 2.22 *NLPM*. Hence, required rate is 480 + 2.22 = 482.22 and at least 500 *NLPM* are needed. It would be recommended to have more *NLPM* and regulate it via a of-rate regulator in any case. Compressed air filling station has been installed in the laboratory in order to recharge the on-board tanks, and they can be utilized to provide air to the platform during the experiments.

The station includes all necessary equipment to fulfill required scenarios and consists of the next parts:

A: 2x300 *bar* storage cylinders. With smart management of the two separate storage tanks $\pm$ 15 fills are possible. The storage tanks are “exhausted” 200 *bar*, but still hold 200 *bar* - 7 *bar* $\times$ 100 l = 19.300 *Nl* for the application with direct connection, which corresponds to roughly 19 *min* $\times$ 1000 *Nl*/*min* of operation at peak consumption.

B: The current distribution is executed in stainless steel tubes 12 $\times$ 2 *mm*, which connect those two tanks with a manual cascade management panel, allowing to select the input (*e.g.* which air storage) to use to fill the portable receiver.

C: The first pressure reducer limits the output pressure to 200 *bar*.

D: The second pressure reducer provides compressed air from 1 *bar* to 10 *bar*, 1600 *Nl*/*min*. From this point on, low pressure components are used to supply the compressed air. In order to minimize pressure loss due to friction, DN20 diameter is used to transport the air.

E: A filling panel enables safe filling of the portable receivers (and drains the hose once the filling is complete to avoid lashing/whipping). In most of other laboratories, Dehumidifier filters are used to dry air. In the big pressurized air tubes (300 *bar*) of Zero-G Lab, the humidity rate is negligible since these tubes are being prepared in the factory environment. Thus, there is no extra need for setting up a dryer into the system.

3.6. Floating platforms

Ground based testing, V&V of the interaction model of two different spacecraft are complex tasks since realizing both GNC and contact dynamics scenarios of two different spacecraft with zero-gravity condition require the usage of high-tech laboratory equipment. To successfully deal with this issue, an advanced mechatronic system, namely the floating platform, is used. The floating platform has pneumatic components called “air-bearing” that blow high pressurized air towards super-flat epoxy floor to cut off the mechanical contact between the air-bearing mounted beneath the floating platform and the epoxy floor. In other words, the floating platform can informally be named as space-drone. Mock-up of space debris or ADR system can be mounted on top of a floating platform [27–29]. Therefore, with two floating platforms, one carrying ADR system and the other carrying space debris mock-up, can be used to verify and validate ADR system’s performance on 2D frictionless plane. In academia and industry, floating platforms have been developed and frequently used by many institutions to mimic and emulate space-related scenarios [30–32].

The floating platform of Zero-G Lab has SIL (Software-in-the-loop) and HIL capabilities, whereas most of the floating platforms existing in the literature do not have SIL and HIL structures. SIL and HIL architectures are needed to realize space interaction scenarios of ADR systems. The floating platforms are integrated with several sensors and can be used for drone-like applications, such as obstacle avoidance, trajectory tracking, path planning, rendezvous under propellant sloshing disturbances and any other GNC application. Thanks to the IP address assigned to the floating platform, onboard sensors can be used for many network applications, such as cloud/edge computing, sensor fusion etc. The floating platforms are connected to the network of the Zero-G Lab as depicted in Fig. 8.

The floating platform has eight nozzles to ensure 3-DoFs movement. Actuating the nozzles with a specific configuration gives the opportunity to drive the floating platform along two translational axes, X and Y, and around one rotational axis Z (yaw axis movement). The endurance of the floating platform depends of the usage frequency of the nozzles. The more frequent the nozzles are used, the less endurance it has. Moreover, adding mass onto the floating platform also decreases the operation time. In general, the endurance of the floating platform for a common GNC application is around 30–40 *min*.

The floating platform can be used to solve critical challenges of satellites’ fuel tank sloshing problem. Mitigating fuel sloshing disturbances during the satellite docking phase is a crucial requirement for enabling on-orbit satellite refueling missions. These missions hold immense promise for extending our reach into deep space, facilitating the exploration and utilization of distant space resources. In these experiments, a floating platform was employed, featuring a sizable tank partially filled with water, emulating the behavior of fuel in a satellite’s tank. One floating platform was tasked with the intricate task of docking with another floating platform equipped with an empty, smaller tank, symbolizing the target satellite in need of refueling. During the docking phase, the presence of fuel sloshing introduces substantial disturbances into the relative motion of these platforms. These disturbances pose a significant risk, as they could lead to unintended collisions between the satellites, potentially resulting in the catastrophic destruction of both spacecraft.

The experimental outcomes arising from the integration of a control scheme combining Model Predictive Control (MPC) and Proportional-Derivative (PD) control techniques are truly noteworthy [33]. These results highlight the exceptional capabilities of the control scheme in terms of trajectory planning and tracking. The control scheme consistently and accurately guides the docking process, ensuring both safety and precision. Moreover, the control scheme’s adept management of thruster activation and fuel consumption emerges as a key advantage. This optimized approach enhances fuel efficiency, thereby enabling the extension of on-orbit satellite missions. These findings underscore the potential of the proposed control scheme to revolutionize on-orbit satellite refueling, opening doors to more extended and ambitious space exploration endeavors.

3.7. Localization and motion tracking system

In order to enhance the capabilities of the Zero-G Lab the following systems have been installed. OptiTrack is a MCS which has been installed in Zero-G Lab. It is used to track the position and attitude of objects in the test area of the laboratory. It is required to provide data for localization, perception, space situational awareness and control. It consists in six Primex 13W cameras capable of operating at rates of up to 240 *Hz* and invisible 850 *nm* infrared illumination. Cameras have standard 3.5 *mm* lens and 850 *nm* bandpass. All six cameras are pointing in predefined directions so that it can cover every angle of the laboratory area. The cameras, hardware and tracker software allows submillimeter real-time localization which is up to the frame rate of the cameras (240 *FPS*). The system operates by tracking small reflective balls, called markers. These markers can be passive (no need of electrical source) or active (need of an power supply). Markers are seen by the MCS cameras, and then the Motive software calculates their respective position through triangulation. As a result, a minimum set of four of such markers need to be attached on different surfaces of the test object in order to fully define a local coordinate system with positional errors less than 0.30 $\pm mm$ and rotational errors less than 0.5 $^\circ$. Motive is the software platform used to control the MCS, allowing the calibration and configuration of the system. Calibration of the MCS is mandatory in order to get accurate results. To do so, the first step is to create masks for static objects that may be in the field of view of each camera. This step is done through the software Motive automatically, and it requires that the laboratory area stays as it is after the calibration process. The second step is to generates more than 15 000 points captured by each of the MCS cameras. A wand made of passive markers is used to that extent. It is necessary to go through all areas of the cameras' field of views. A last step consists in creating the origin coordinates of the laboratory area. A special calibration square with active markers is to be set at one corner of the area. Once the calibration is done, Motive also provides an interface for both capturing and processing 3D data. Motive senses 3D information via reconstruction, which is the process of compiling multiple 2D images of markers to obtain 3D coordinates. Using 3D coordinates from tracked markers, Motive can obtain 6-DoFs (3D position and orientation) data for multiple rigid bodies and enable tracking of complex movements in the 3D space. The tracking data can be derived and filtered in real time to generate velocity data.

3.8. Illumination

The generation of realistic sun lighting conditions (like in space) plays an important role, especially concerning the reproduction of light with the sun's irradiation intensity and spectrum. As a requirement for sun emulation, it was aimed to achieve the same irradiance of approximately 1.35 kW/m^2 as the sun has at an earth orbit [34], with the illuminated target size estimated to be more than 3 $m \times 3$ m. In addition, a sun-like spectral power distribution should be present in the visible region of the light spectrum. Also, the challenging lighting conditions in space, such as oversaturation of sensors, harsh contrasts, and the loss of colour information have to be recreated.

Accordingly, a Godox SL-60 Video Light [35,36] is used for lighting, to replicate orbital scenarios at the facility. It is a 60 *W* LED light with dimensions 23 $cm \times 24$ $cm \times 14$ cm and temperature of 5600 *K* corresponding to daytime sunlight [37]. Two light source modifiers, a collimator and a reflector, are also available for simulating various illumination conditions from a space environment. For example, collimators, producing parallel light beams that create hard shadows and significant differences in light intensity between illuminated and dark regions, are typically chosen for mimicking objects in space illuminated by the sun without an atmosphere [38]. The lamp can be mounted on the robotic arms for mimicking dynamic illumination scenarios or placed static on a tripod. In the future development of the facility, it is also planned to use additional lighting sources, like light boxes, for simulating earth's albedo [39].

3.9. Vision sensors

The FLIR Blackfly S BFS-U3-16S2C camera [40] is used to capture RGB images for testing vision-based space applications at the facility. The camera is a lightweight ($<$50 *g*) and cost-effective solution for space-sensitive imaging applications. It has different features, including precise control over exposure, gain, white balance, and colour correction, making it ideal for machine vision systems. Also, FLIR's Spinnaker Software Development Kit (SDK), camera Application Programming Interface (API) documentation and existing codebase provide extensive support for developing new imaging applications. FLIR Blackfly S cameras are GenICam [41] and USB 3 Vision [42] standards compliant making them suitable for easy integration with other software and hardware systems. Based on the emulated orbital scenario, the camera can be installed as a payload on the robotic arms or on a tripod. In addition to the camera, two different types of fixed focal lenses (6 *mm* and 12 *mm*) are also used. The lenses are designed for pixels that are $\leq 2.2 \mu m$. They provide high levels of resolution ($>$200 lp/mm) across the sensor and are compatible with all standard C-Mount cameras.

3.10. Experiment monitoring

The lab uses three 5 Megapixel Reolink RLC-422 dome camera with 4x optical zoom IP cameras for real-time viewing and recording of experiments. The Reolink software allows the visuals to be panned and zoomed. They are also used to track the position and attitude of every piece of equipment within test area. The data is streamed using WLAN of the laboratory.

4. Setup of the Zero-G Lab

Fig. 8 describes the robotic network realized in the Zero-G Lab facility. Each robotic arm and rail is connected to the robotic network using Ethernet cables. To control the robots, Universal Robots ROS driver [43] implemented as a part of the Zero-G Lab's ROS control framework, is used. The robotic rails are controlled via an in-house implementation of a ROS-control [44] based driver.

The control PC depicted by ROS Control computer acts as the ROS master and is used to run the nodes related to the operation of robots and rails. Vision based ROS nodes are launched separately from another computer called the Vision PC. It is possible to connect any ROS compatible machine (PC, robot, or floating platform) to the network. The data from the MCS cameras (connected over a different network) are accessible in ROS using appropriate commands. The entire robotic Setup in the Zero-G Lab is visualized in the native ROS visualization environment RViz, as shown in Fig. 7.

On top of RViz interface, a simulation setup in Gazebo physics engine has also been developed to test and validate various algorithms prior to running them on real robots in the facility. Various applications in motion planning, manipulation and perception are be realized via the MoveIt setup realized for the facility. Motion of each robotic arm can be planned independently.

5. Using the Zero-G Lab for in-orbit experiments

Various experiments emulating on-orbit conditions may be conducted in the Zero-G Lab. The two robotic arms and the floating platforms are leveraged for mounting satellite mock-ups and emulating several spaceflight motions.

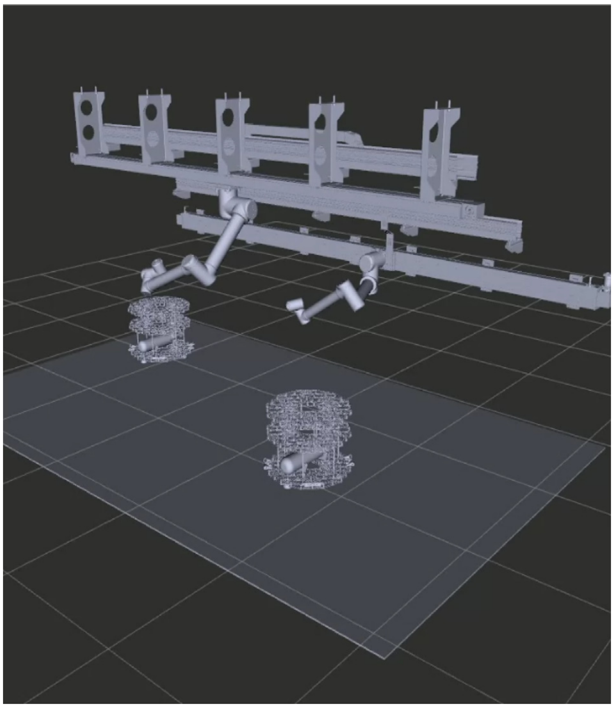

Fig. 7. RViz interface of Zero-G Lab.

5.1. Open-loop tests

5.1.1. Validation of pose estimation algorithms

Flight paths for various missions, in near-Earth space and deep space, are offered as baseline paths for the robotic arms to emulate satellite motion. The motion of a target satellite, mounted on one of the robotic arms, is captured through a camera mounted on the other. Consequently, images captured by the camera are processed to identify the relative pose between the two satellite mockups (one of them is the camera). Different types of pose estimation algorithms may be verified with such a setup. Furthermore, varying lighting conditions and separation distances also offer diverse data to analyze. Testing the limits of the algorithms with only a partial view of the satellite or a complete loss of image may be further emulated.

5.1.2. Standalone trajectory emulation

An open loop trajectory for the satellite path, both in position and orientation may be emulated without additional feedback leveraging satellite mockups mounted on robotic arms. Such trajectories typically are not based on visual feedback but rather serve as a reference guidance path for designing experiments and eventually assist in designing HIL experiments by accounting for limitations in the accessible workspace and lighting conditions.

5.2. Closed-loop tests

5.2.1. HIL rendezvous

A 7-DoFs motion to emulate chaser and target spacecraft dynamics during rendezvous and docking can be leveraged using two robotic manipulators used in synchrony. The chaser and target are mounted at the end-effector of the two robotic manipulators and appropriate waypoints are delivered to emulate the position and orientation. A GNC algorithm, pose estimation algorithm with servoing operating in tandem enables a complete HIL emulation of spacecraft rendezvous. The concept for cislunar rendezvous with a GNC algorithm that incorporates coupled orbital dynamics and attitude dynamics in the circular-restricted three-body problem was demonstrated [5,6]. These experiments were conducted in the Zero-G Lab. Rendezvous in circular Earth orbits have exploited

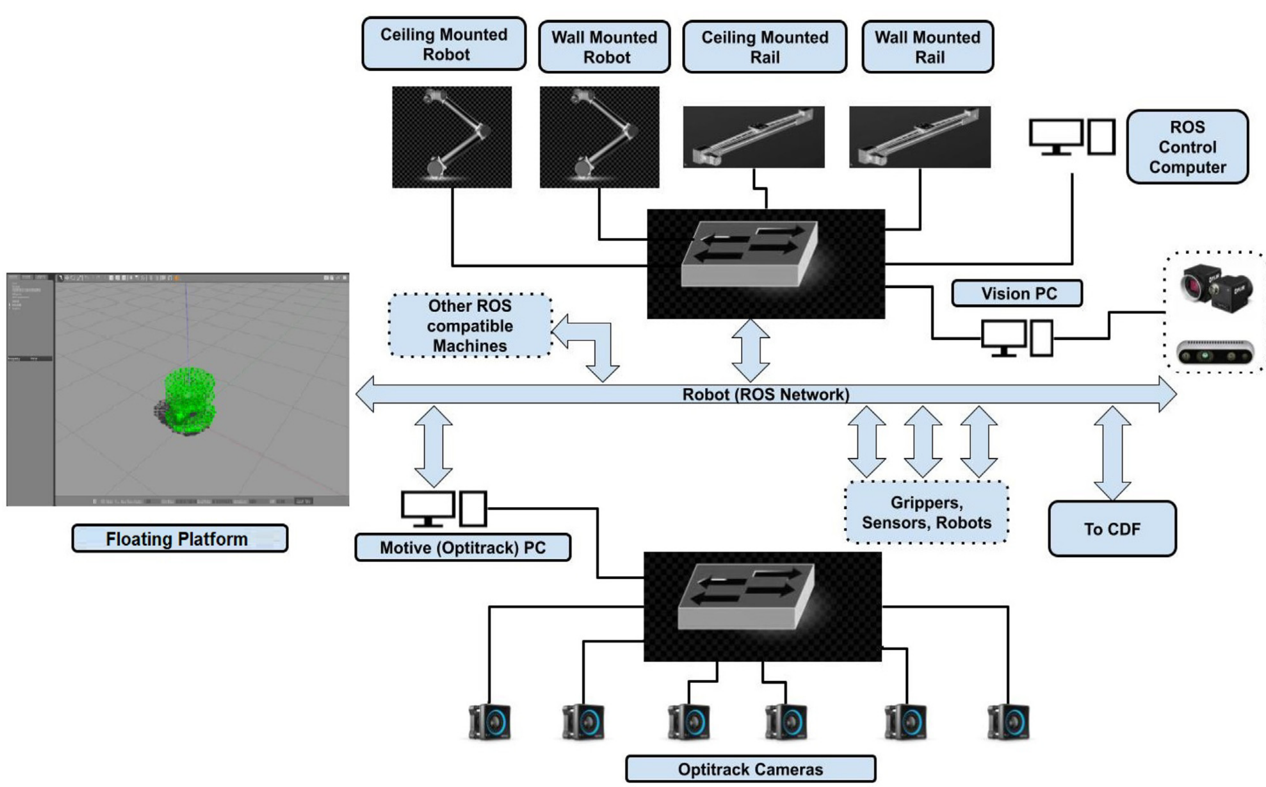

Fig. 8. Setup of the robotic network.

Clohessy-Wiltshire equations of motion for the relative dynamics [45]. Such a concept has also been tested with HIL at the EPOS test facility by [8,46].

5.2.2. On-orbit interaction

The contact dynamics between objects in space are different from that on Earth. Equations for orbital dynamics for the satellite mockups that incorporate feedback in the form of force and torques during contact potentially deliver the satellite motion in a microgravity environment. The F/T (force and torque) sensors on the robot tool center measure force and torque during any contact with the satellite mockup, and subsequently translates their effects on satellite position and orientation. The updated pose parameters are delivered as the necessary waypoints to emulate satellite dynamics. In [47], on-orbit interactions using a cartesian motion controller in the Zero-G Lab were demonstrated. The experiment includes a controlled collision between two satellite mockups mounted on two robotic manipulators. Force and torque values acting on both spacecraft alter their motion post-collision. In addition, the floating platforms may be used to deliver any motion dominant in a 2D plane or the robotic arms for a complete 3D motion with position and orientation. Force and momentum transfers during contact account for a change in flight trajectory and orientation.

5.2.3. Lander

Using either the floating platform or the robotic manipulators in the Zero-G Lab, the controlled actuation of the landing module can be evaluated. A two-dimensional motion is reproduced using the floating platform while the robotic manipulator offers a three-dimensional motion for the landing module. The air nozzles on the floating platform resemble the thrusters on the landing module and are analogously actuated to deliver appropriate motion, both in translation and orientation. A two-dimensional motion is planned, one in the direction of gravity and another perpendicular to the direction of gravity. Such a motion is achieved by enabling the planar motion of the floating platform along the epoxy floor in the laboratory. The robotic manipulators however do not possess an active thrusting capability, rather appropriate three-dimensional way-points (in translation and orientation quaternions) are delivered to achieve motion. For convenience, the longer dimension of the laboratory is chosen to serve the lander motion in the direction of gravity in both cases. The control algorithm identifies appropriate maneuvers to satisfy certain target conditions, both in trajectory and attitude. Feedback for its position and orientation is delivered using the MCS markers mounted on the floating platform in either case. Such closed-loop state feedback enables corrective maneuvers to be incorporated. Scaling factors may be used to simulate larger distances. Depending on the landing surface (such as the Moon, Mars, asteroids, etc.) and applications, relevant parameters such as gravity may be modified.

In addition to the mentioned tests, the microgravity research facility provides an opportunity to conduct various mission-specific tests that leverage robotic arms and floating platforms in the Zero-G lab. Mission-specific tests conducted within the research facility allow the exploration of the specific challenges and requirements in a controlled environment. By leveraging the unique features of the Zero-G lab, we can ensure that the systems and procedures are well-adapted to the complexities of space environments, leading to a higher likelihood of mission success.

5.3. Safety of operations

From a safety standpoint, the laboratory plays a crucial role in testing extreme space environments, as exemplified in the study by Muralidharan et al. [48] at the Zero-G lab. This research focuses on vision-assisted satellite rendezvous operations, particularly in challenging lighting conditions. Ensuring safety during such experiments is a multifaceted process, incorporating both software-based and hardware-based safety measures.

Software-based safety measures involve the implementation of various filters and parameter adjustments to mitigate unpredictable factors. For instance, the utilization of a Kalman filter for pose observations helps enhance the precision of satellite control. Fine-tuning the parameters governing satellite motion control is another essential aspect of ensuring the safe operation of satellites during tests. These software-based measures are primarily oriented toward controlling and monitoring the actual motion of satellites.

On the other hand, hardware-based safety limits pertain to the operability of the robotic hardware within the laboratory environment. Given that satellite motion is not confined to the lab's boundaries, there may be situations where robots cannot accurately deliver appropriate satellite states or, conversely, provide unwarranted satellite states. These issues may arise due to workspace limitations or potential interference with other equipment in the laboratory. To address such challenges, the hardware architecture incorporates clearly defined safety limits and workspace boundaries. Additionally, the use of 'manipulability index' and 'Jacobian Condition Number' for classifying robot joint states is employed as a measure of safe robot motion [48], to effectively manage these safety constraints.

The laboratory's safety protocols encompass a comprehensive approach, encompassing both software and hardware-based strategies, to ensure the secure testing of extreme space environments and satellite operations. The combination of filters, parameter adjustments, and well-defined hardware boundaries contributes to the overall safety and success of these critical experiments. Such a framework is similarly applied across various other tests conducted within the laboratory.

6. Conclusion

In this study, a comprehensive review of orbital robotic labs from different institutions has been conducted. The construction and setup of the Zero-G Lab have elaborately been described. The relation of each system component, robotic manipulators, floating platforms, MCS, and IP cameras are described in terms of perception and control topics. A few mission-specific tests such as rendezvous and docking, on-orbit interaction, landing, etc., that leverage robotic arms and floating platforms in the Zero-G lab are briefly discussed. Therefore, the paper can inspire researchers to get a deeper insight into the HIL and SIL realization and emulation of orbital robotics scenarios in laboratory conditions. The study can be used as a set of guidelines for the construction of similar facilities while it can motivate companies to test, verify and validate their products up to TRL-6 (technology demonstrated in relevant environment, industrially relevant environment in the case of key enabling technologies) before product's full commercialization, therefore companies can minimize any financial or relevant risks.

Additional test cases will be conducted in various projects, such as ESA funded DragLiner project [49], within the scope of Zero-G Lab. Prior experiments conducted in the Zero-G Lab are listed throughout the paper [5,6,30,32,36,47,48,50].

Declaration of Competing Interest

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.

CRediT authorship contribution statement

Miguel Olivares-Mendez: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mohatashem Reyaz Makhdoomi:** Methodology, Software, Validation, Investigation, Data curation, Writing – original draft. **Barış Can Yalçın:** Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Zhanna Bokal:** Conceptualization, Methodology, Software, Investigation, Resources, Writing – original draft, Writing – review & editing. **Vivek Muralidharan:** Software, Investigation, Writing – original draft, Writing – review & editing. **Miguel Ortiz Del Castillo:** Conceptualization, Methodology. **Vincent Gaudilliere:** Conceptualization, Methodology, Software, Validation, Investigation, Supervision. **Leo Pauly:** Methodology, Software, Validation, Investigation, Writing – original draft. **Olivia Borgue:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Mohammadamin Alandihallaj:** Methodology, Software. **Jan Thoemel:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **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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