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Europe's Flattest Floor

In July of 2022, I was contacted about installing one of my Precision Air Bearing Floor Systems in the UK at the new ZERO-G Astrolab Robotics Laboratory at the University of Liverpool. I would be working on the REMORA Project, info at this link - https://gtr.ukri.org/projects?ref=MR%2FW009498%2F1 - with Dr. Stefania Soldini and her team. She had referenced the European Space Agency's European Space Technology and Research Centre in the Netherlands as an example of what she was looking for, this testing facility is billed as 'Europe's Flattest Floor', info at this link - https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Zero-G_Europe_s_flattest_floor After reviewing the specifications on that floor, I assured Dr. Soldini that her new Laboratory would be the next level in comparison. The next 3 years was spent consulting with Dr. Soldini and her team, advising the general contractor on specifications for the renovation of the basement Laboratory in the 200 year old George Holt Building on campus and the ever exhausting time spent with the administrative process of contracting a project of this importance. Finally in mid August of 2025 we were on site setting up to start this installation that lasted until mid September, info at this link - https://www.liverpool.ac.uk/research/space/space-robotics

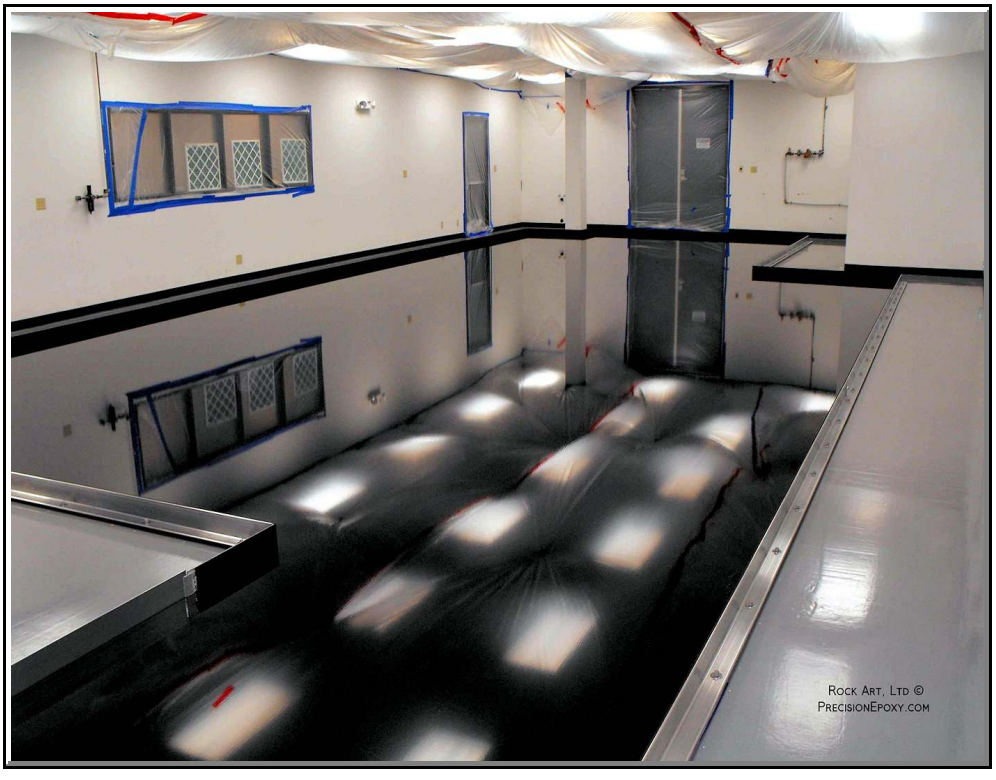
After installation was completed, the metrology crew from Manchester Metrology was brought in to conduct laser tracker testing and measurements on our floor and the results revealed that the University of Liverpool ZERO-G Astrolab now has the 'Europe's Flattest Floor' by a big margin.

ESA's ESTEC floor	Maximum inclination / Level	< 0.3 mm/m or 0.01181102 inch
Precision Epoxy floor	Maximum inclination / Level	< 0.022 mm/m or 0.00086614 inch
ESA's ESTEC floor	Overall Flatness	< 0.8 (± 0.1) mm or 0.03149606 inch
Precision Epoxy floor	Overall Flatness across the whole floor	< 0.27 mm or 0.01062992 inch
Precision Epoxy floor	Overall Flatness at points throughout usable test area	<1e-2mm or 0.0003937 inch

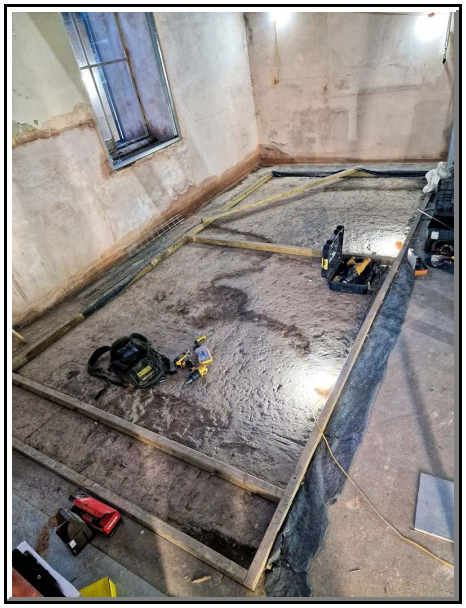
Note: The higher spots measured across the whole floor are the meniscus curve in the upper surface of the liquid epoxy, produced by surface tension, close to the vertical surface of the outer retaining wall which is not realistically usable test area of the floor.

This makes the ZERO-G Astrolab Robotics Laboratory at the University of Liverpool floor 80 times flatter and 13.6 times more level than the ESA's ESTEC floor.

The size of the ESA's ESTEC floor is 4.8 m x 9 m (15.75 ft x 29.5 ft or 465 square feet).
The size of our Precision Air Bearing Floor System in the University of Liverpool's ZERO-G Astrolab is 2.4 m x 5.2 m (8 ft x 17 ft or 136 square feet). For the skeptic individuals who assume that the smaller size (3.4 times smaller) may contribute to the overwhelming accuracy differences, rest assured there is no truth to this correlation. Our Precision Air Bearing Floor Systems are far superior to any other alternative regardless of the size. One example is our 1100 square foot installation at Northorp Grumman for the University of Southern California in December of 2008 (over 2.3 times the size of the ESA's ESTEC floor). The USC Project has similar accuracy numbers to that of the ZERO-G Astrolab.



Start to finish on the renovation of the ZERO-G Astrolab and installation of the Precision Air Bearing Floor System with variance of substrate inclination from left front corner to back right corner.



See the ZERO-G Astrolab in operation here - https://www.youtube.com/watch?v=n6PqhiFiS7U
Special thanks to all the fine people at the University of Liverpool involved with this project. Their help with getting me moved in and set-up to do the installation was instrumental to our success. My appreciation and respect go to Justin Jamieson, owner of JCE Custom Epoxy Resins, https://jcecustomepoxyresins.co.uk, Justin assisted me on this project and is our UK representative.

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Development of the Zero-G AstroLab: A GNC Testbed for Autonomous Deep Space Exploration

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***Abstract*—Deep-space operations in proximity to small celestial bodies present significant challenges for spacecraft Guidance, Navigation and Control (GNC) due to weak and highly irregular gravitational environments. Tasks such as mapping, imaging, landing, touchdown, and sampling require high levels of onboard autonomy, as communication delays limit real-time ground intervention. The development of autonomous robotic technologies for these missions therefore requires extensive ground-based validation prior to deployment. This paper presents the University of Liverpool's Zero-G Astrodynamics Laboratory (Zero-G AstroLab), a dedicated 60 m^2 microgravity test facility developed within the UKRI-funded REndezvous Mission for Orbital Reconstruction of Asteroids (REMORA) project. The facility is designed to support the development and validation of autonomous spacecraft robotics and GNC technologies for asteroid proximity operations and planetary defence missions. At its core is a 5 $\times$ 2.5 m ultra-flat precision epoxy air-bearing floor. Laser-tracker measurements indicate an overall floor flatness of 0.27 mm, with a mean point-wise deviation of 0.041 mm from the best-fit plane, enabling high-fidelity emulation of free-floating spacecraft dynamics. Additional infrastructure includes a Qualisys motion-capture system, analogue terrain environments, and free-floating robotic platforms for hardware-in-the-loop testing of autonomous spacecraft operations. Although primarily developed for asteroid proximity operations and planetary robotics, the facility can support spacecraft proximity operations, rendezvous and docking, in-space manufacturing, and distributed spacecraft systems. This paper presents the design and implementation of the laboratory, the development of its free-floating robotic platforms, and the experimental validation of the facility.**

***Index Terms*—Hardware-in-the-Loop Testing, Guidance, Navigation and Control, Air-Bearing Testbed, Autonomous Space Systems, Asteroid Proximity Operations.**

I. Introduction

Small celestial bodies, including asteroids and comets, are increasingly becoming targets of scientific exploration and planetary defence missions. Their low-gravity environments offer unique opportunities for *in-situ* investigation but also present significant challenges for spacecraft Guidance, Navigation and Control (GNC) systems. Spacecraft operating in proximity to these bodies must perform complex tasks such as gravity measurements, imaging, station-keeping, landing, touchdown, and sampling while navigating highly irregular gravitational fields and uncertain environmental conditions.

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The large communication delays associated with deep-space missions further limit the possibility of direct ground intervention, requiring critical mission phases to be executed autonomously. Consequently, the development of robust autonomous robotic systems has become a key enabling technology for future small-body exploration missions. However, the validation of these technologies prior to flight remains a major challenge. While numerical simulations provide a flexible development environment, they cannot fully capture the effects of sensor and actuator uncertainties, contact dynamics, and hardware interactions. Ground-based experimental facilities capable of reproducing key aspects of microgravity dynamics are therefore essential for the development, testing, and verification of autonomous spacecraft systems.

The Zero-G AstroLab was developed as part of the UKRI-funded REMORA project [1], a seven-year research programme focused on planetary defence missions and autonomous GNC technologies for asteroid proximity operations. REMORA investigates a novel mission concept based on a fleet of CubeSats operating in close proximity to asteroids to improve orbit determination, characterisation, and long-term monitoring of potentially hazardous objects [1]. The project addresses the development of autonomous onboard GNC algorithms required to support future distributed asteroid exploration and planetary defence missions.

Several ground-based facilities have been developed around the world to support research in on-orbit space operations. These operations, such as rendezvous and docking, active debris removal, and spacecraft proximity operations through the use of robotic platforms, are validated using hardware-in-the-loop (HIL) simulations. Generally, these facilities enable HIL capabilities through various mechanisms such as robotic platforms [2], suspension systems [3], cable robotics [4], neutral buoyancy [5], and air-bearing systems. Air-bearing mechanisms provide numerous advantages over other methods such as the capability to observe dynamic effects experienced by the spacecraft due to space actuator operations such as reaction wheels and control moment gyroscopes, operation of robotic arms for proximity operations, and free-floating contact dynamics. Some of the widely known facilities that use air-bearing mechanisms for HIL simulations include the European Space Agency (ESA)'s ORBIT facility [6], the US Naval

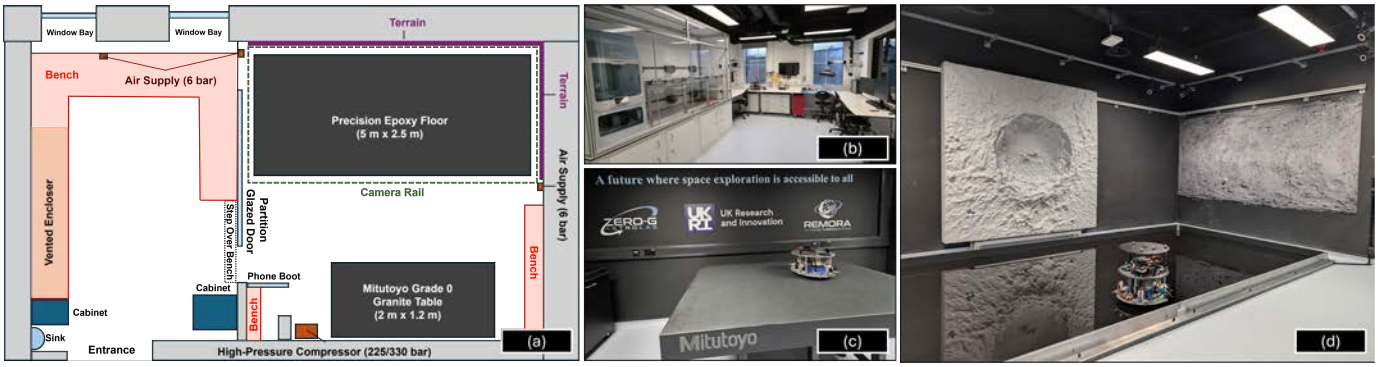

Fig. 1: (a) Floor plan of the Zero-G AstroLab, (b) Manufacturing and control room area, (c) Mitutoyo Grade 0 granite table, and (d) Main test arena: 5 m $\times$ 2.5 m Precision Epoxy air-bearing floor with mock-up terrain panels and a Qualisys MCS.

Postgraduate School's POSEIDYN testbed [7], the University of Luxembourg's Zero-G Lab [8], German Aerospace Center (DLR)'s EPOS, TRON and TEAMS facilities [2], [9], [10], Georgia Institute of Technology's ASTROS facility [11], the University of Florida's ADAMUS testbed [12], and Caltech's Autonomous Robotics and Control Lab [13]. Such facilities have significantly advanced the development and validation of autonomous GNC systems for orbital applications through high-fidelity HIL simulations for analysing and validating the highly dynamic operations in extreme space environments. However, most facilities primarily focus on autonomous proximity operations such as spacecraft interaction experiments for rendezvous and docking, orbital robotics using space manipulator systems, contact dynamics research, and formation-flying studies. Comparatively fewer facilities have been specifically designed to support autonomous planetary robotics research such as small-body navigation, autonomous touchdown, landing, surface interaction, and sampling manoeuvres under microgravity conditions. To address this gap, the Zero-G AstroLab, developed at the University of Liverpool, combines a mission-driven focus on asteroid exploration and planetary defence with an ultra-flat Precision Epoxy [14] air-bearing floor technology. The Zero-G AstroLab combines the ultra-flat air-bearing floor with free-floating robotic platforms, precision motion-capture infrastructure, and rapid-prototyping capabilities to enable high-fidelity hardware-in-the-loop testing of spacecraft proximity operations and planetary robotics technologies. This paper presents the design and implementation of the Zero-G AstroLab facility, the development of its free-floating robotic platforms, and the experimental validation of the laboratory.

II. Zero-G AstroLab Facility Design

As future planetary defense and deep-space exploration missions increasingly rely on autonomous decision-making and proximity operations, the need for realistic ground-based validation environments becomes critical. This section presents the design drivers of the Zero-G AstroLab.

A. Facility Overview

The Zero-G AstroLab is a 60 m^2 research facility located in the basement of the George Holt Building at the University of Liverpool. The laboratory comprises a manufacturing area for the rapid prototyping, assembly, and testing of robotic platforms (left area in Fig. 1a), and a dedicated 5 m $\times$ 2.5 m ultra-flat Precision Epoxy air-bearing floor for microgravity experimentation (right area in Fig. 1a).

The facility is equipped with a compressed-air distribution system operating at 6 bar, with outlets located in both the manufacturing and experimental areas. These outlets support the operation of the in-house developed air-bearing platforms, termed BEATLE (Bearing-free Experiment for an Autonomous Testbed in a Low-gravity Environment), as well as laboratory maintenance activities.

The manufacturing area includes additive manufacturing equipment and a vented machinery cabinet, enabling the rapid fabrication and assembly of robotic hardware components, as shown in Fig. 1b. Figure 1b also shows the laboratory workbenches, a soldering station equipped with a Nederman benchtop extraction arm, and the ground-station workstation. The workstation hosts an in-house developed telemetry and communication framework that provides bidirectional wireless communication with the BEATLE platforms, supports real-time command and control, integrates motion-capture measurements, and enables experimental data logging for hardware-in-the-loop testing.

B. Precision Air-Bearing Floor

The Zero-G AstroLab incorporates a Precision Epoxy air-bearing floor system, representing the first European installation of this technology for spacecraft robotics and microgravity research since its deployment at the McLaren Technology Centre in 2021 for automotive engineering applications. Developed for environments requiring ultra-flat and highly stable surfaces, the technology has been adopted in advanced aerospace, robotics, manufacturing, and scientific research facilities where air-bearing systems demand exceptionally stringent flatness tolerances. Precision Epoxy technology was selected for its

established use in spacecraft dynamics testbeds and compatibility with commercially available flat air bearings, including those manufactured by New Way Air Bearings.

The floor was delivered as a turnkey installation, encompassing substrate preparation, construction, and final metrology verification. Following preparation and sealing of the existing concrete substrate, successive self-leveling epoxy pours were applied within a temporary retaining frame until the required flatness was achieved. The installation also incorporated an embedded antistatic grounding system and permanent aluminium perimeter edging. Figure 2 illustrates the principal stages of the floor construction process, including substrate preparation (a)–(b), grounding-grid installation (c), and the completed Precision Epoxy surface following the final pours (d).

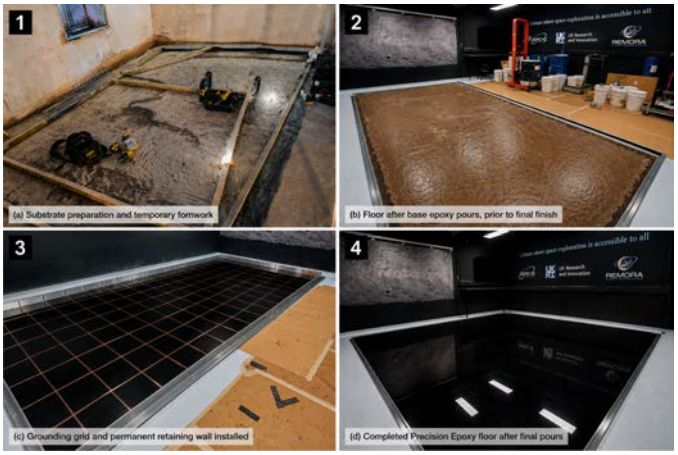

Fig. 2: Construction stages of the Zero-G AstroLab Precision Epoxy air-bearing floor: (a) preparation of the concrete substrate and temporary formwork, (b) floor after the initial epoxy pours prior to the final finishing layers, (c) installation of the conductive grounding grid and permanent retaining wall, and (d) completed air-bearing floor following the final self-leveling epoxy pours.

C. Floor Metrology

Compliance of the floor with the design requirements was independently verified by Manchester Metrology using laser-tracker (Leica AT600) measurements (see Fig. 3). The survey assessed both the surface flatness and the overall gravitational level of the test area. The results indicate an overall floor flatness of 0.27 mm across the 5 m $\times$ 2.5 m operational area, with a mean point-wise deviation of 0.041 mm from the best-fit plane and a peak-to-valley variation of approximately 0.30 mm. The maximum measured inclination was 0.022 mm/m, ensuring negligible gravity-induced drift during air-bearing experiments.

The experimental area in Fig. 1d is maintained under controlled cleanliness conditions, as dust particles can adversely affect air-bearing performance. A step-over bench (as marked in Fig. 1a) is installed at the entrance to the experimental area to prevent external contamination, while protective shoe

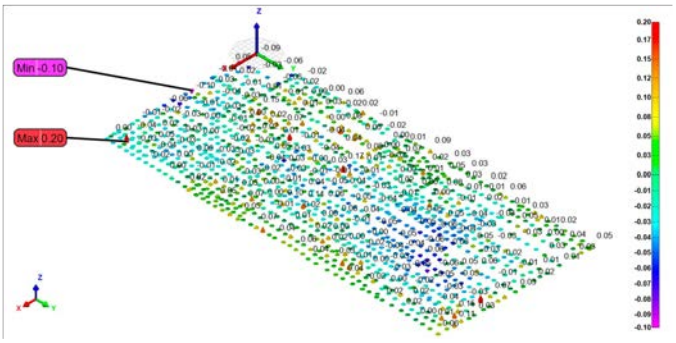

Fig. 3: Laser tracker-based flatness map for the air-bearing floor showing point-wise deviations from the best-fit plane. (Units in millimetres.)

covers and laboratory suits are required when accessing the test floor. Regular cleaning procedures are performed to maintain the surface quality of the epoxy floor, Fig. 1d.

D. Motion Capture and Experimental Infrastructure

The test arena surrounding the epoxy floor combines a Qualisys motion-capture system (MCS) and mock-up terrain mounted on walls. The Qualisys MCS comprises of 8-camera set-up of 4 x Miqus M3 (standard lens), with 4 x Miqus M3 (wide lens) and a 1 x Miqus High Speed Colour Video Plus with camera rail in green dashed line Fig. 1 (a). The cameras are located at the corner of the test arena two per each length of the floor while the video camera is located in the middle of the partition wall. The system is portable and can be used to capture smaller volumes for example to be used for the granite table top by installing three cameras on heavy duty tripods. The system includes a dedicated workstation and license for Qualisys Track Manager (QTM). QTM allows for the calibration of cameras within the target volume using a 300 mm wand kit and fixing the coordinate frame origin to a specific point in the volume using a L-frame. Using the QTM software, target objects with unique marker configurations can be identified as 6-DOF bodies with their own coordinate frames, allowing for precise frame definitions of the inertial and body frames.

The School of Engineering workshop at the University of Liverpool manufactured four mock-up terrain panels, each measuring 2 $\times$ 1 m, using a 7-axis KUKA robotic machining arm as shown in Fig. 4. The panels were machined from polyurethane tooling board and installed along the 5 m length of the epoxy floor. These terrain models provide representative planetary surface features for optical navigation testing, landmark-based navigation, and proximity-operation experiments. The panel shown in Fig. 1d reproduces a section of NASA's Copernicus lunar crater terrain.

The facility also includes a Mitutoyo Grade 0 granite table measuring 2 $\times$ 1.2 m shown in Figure 1c. The table provides a secondary high-precision experimental surface for sensor calibration, component testing, platform assembly, and small-scale robotics experiments. The portable Qualisys motion-capture

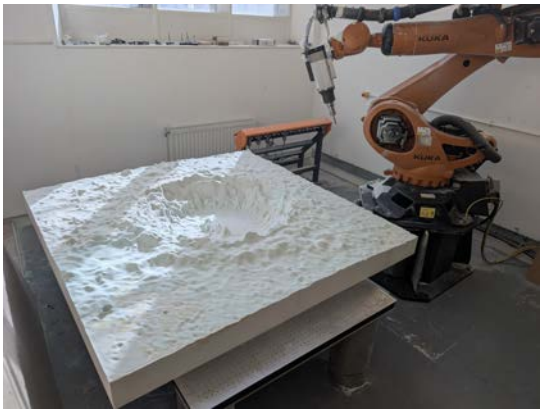

Fig. 4: KUKA machining arm.

TABLE I: BEATLE Platform - Baseline Specifications

Category		Specification
Floating Platform	**Air bearings**	New Way air bearings, 40 mm, 3 units
	Pneumatics	Compressed-air cylinder, 2 L @ 300 bar
	Working pressure	5.5 bar for air bearings and thrusters
	Operating time	Approximately 30 min
Spacecraft Emulator	**Size**	BEATLE-I – 42 cm dia. × 50 cm height BEATLE-II – 12U or 23×23×34 cm
	Mass	Approximately 12 kg
	Main PC	NVIDIA Jetson Orin Super Nano
	Microcontroller	Arduino GIGA R1
	Sensors	Adafruit BNO085 IMU, 5.5 bar Pressure Sensor
	Electrical interface	UART, USB, GPIO, SPI, I^2C, I^2S, WLAN, CSI
	Power	12 V input; 5 V and 3.3 V regulated supplies; approximately 30 W maximum
	Payload	Navigation camera - Arducam Sony IMX219

system can be reconfigured around the granite table using tripod-mounted cameras, enabling accurate tracking within smaller experimental volumes.

The facility also includes a Nardi Atlantic 100 high-pressure compressor equipped with 225 bar and 330 bar filling connections for the refilling of compressed-air cylinders used by the air-bearing platforms. This capability provides an independent on-site air supply, supporting continuous testing and reducing downtime between experimental campaigns.

III. Free-Floating BEATLE Platforms

A. Overall Design

BEATLE-I and -II are free-floating robotic platforms designed to emulate the planar motion of small spacecraft in a ground-based low-gravity environment. Both platforms share the same baseline architecture. BEATLE-I is developed as an initial rapid-prototyping and educational platform, whereas BEATLE-II was developed in a smallsat design, a compact 12U-class for high-precision GNC algorithm validation in alignment with the REMORA project goals. The baseline specifications for the platforms are summarised in Table I. Each platform consists of air bearings for minimising friction on the precision epoxy floor, an onboard computer, a low-level microcontroller, attitude and state sensors, a compressed-air-based propulsion system, and a wireless communication link with the ground station. The air bearings enable planar translational and rotational motion, while the compressed-air system is commonly used for both air-bearing levitation and cold-gas thruster actuation. The onboard electronics integrate the camera, IMU, pressure transmitter, thrusters, and reaction-wheel interface, while the ground station transmits tele-commands and receives telemetry through a Wi-Fi-based TCP/IP communication link.

B. Mechanical Design

The platforms are designed in a way to ensure ease of assembly and maintenance with a lightweight yet strong structure. Commercial-of-the-shelf components are prioritised, allowing for low-cost reproducible architecture. However, the primary chassis for both platforms is designed separately for achieving the individual goals of each platform. For BEATLE-I, a reconfigurable architecture with an expandable design was developed such that more layers can be installed to increase the number of components. Furthermore, each level is constructed using an identical 4 mm aluminium plate with a diameter of 420 mm, allowing for levels to be interchanged. All the plates include M6 holes in a 25 mm grid, allowing for flexible placement of the components. This design allows for fine-tuning the platform centre of mass by strategically placing the components. Furthermore, 3D-printed fixtures allow for easy installation of components. This methodology allows for

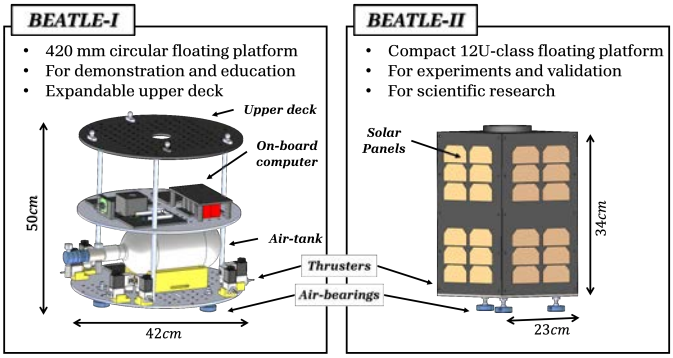

Fig. 5: CAD Model of the BEATLE Platforms

ease of construction and assembly throughout the platform. For BEATLE-II, a more precise methodology is devised to achieve the scientific goals. The primary structure is built using 20 mm$\times 20$ mm aluminium profiles to constrain the size of the platforms. Furthermore, this structural design offers to build a layered structure inside using brackets along the profiles. The tank is placed in the centre of the platform vertically with all the electronics on the internal walls of the platform. The lower level is reserved for the thruster assembly and a reaction wheel. In this case, most of the fixtures are machined using aluminium for precise positioning of the thruster assembly to avoid inducing asymmetric force/torque due to machining errors. The overall CAD design for both platforms is shown in Fig. 5. The overall mass and inertia for BEATLE-I is $m = 13.607$ kg and $I_z = 0.2686$ kg $\cdot$ m^2

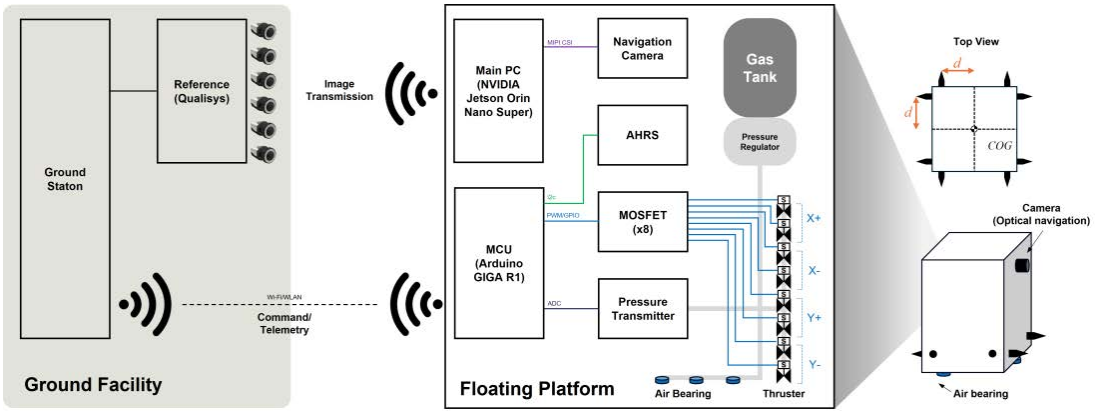

Fig. 6: Overall System for Ground Facility, Floating Platform and Layout

C. Propulsion and Pneumatic system

Both platforms are actuated using three identical 40 mm New Way air-bearings which are supplied using a constant air-pressure of 5.5 bar. Since the weight of the platform is well within the air-bearing ratings, the air-bearings do not lose pressure and work within operating range when the thrusters are fired. For the thruster assembly, both platforms use identical mechanisms using eight Silvent MJ40 air nozzles with high-precision air-flow and blowing force of 1 N at 5.5 bar. Each thruster nozzle is actuated using an independent 2/2 way normally closed solenoid valve operating at 12 V. The solenoid valve operation is controlled using two 4-channel MOSFET relay boards that are commanded the on-off configuration for all thrusters via the on-board low-level controller. Pressurised air for the platforms is provided by the HK Army Alpha Air Tank filled up to 1.6 L at 300 bar. The air pressure is regulated to 5.5 bar via a 2-stage system: the HK Army HP8 regulates the pressure to 55 bar, and then the HK Army Hostile XLP provides fine adjustment from 0-10 bar using an Allen-key knob and micro gauge. To ensure precision, a pressure sensor is used to control of the output pressure to 5.5 bar. Finally, a 4 mm ID tube is used as the standardised air-supply line throughout the platforms. The thruster layout as shown in Fig. 6 is designed to allow for control authority in all 3 degrees-of-freedom (DOF). The separation distance from the centre of the platform is set as $d = 114$ mm for BEATLE-I and $d = 57$ mm for BEATLE-II. Using this configuration, two thrusters can generate a combined 2 N along each axis in the $x - y$ plane. For the yaw control, four thrusters can generate a combined yaw torque of $\tau_z = 456$ mNm for BEATLE-I and $\tau_z = 228$ mNm for BEATLE-II.

D. Avionics and Software Architecture

The avionics and software architecture of the BEATLE platforms is designed to functionally separate high-level computation, low-level real-time control, and ground-station communication. The high-level onboard computer is based on the NVIDIA Jetson Orin Nano series and is responsible for image processing, navigation algorithms, experimental data handling, and Wi-Fi communication with the ground station. Low-level control is performed by an Arduino GIGA R1 or an equivalent microcontroller, which handles time-sensitive functions such as thruster commands, sensor updates, pressure measurements, and the reaction-wheel interface. The flight software is implemented as a lightweight task-oriented framework without relying on an external operating system. It uses timer-driven cooperative scheduling, in which each task is periodically executed within the main loop. The baseline tasks include telecommand parsing, thruster control, IMU updates, and telemetry transmission. The ground station transmits commands and receives platform state data through a TCP/IP-based packet protocol, where each packet consists of a header, packet length, variable-length payload, and CRC. This architecture improves communication reliability while allowing the same software framework to be reused and extended across BEATLE-I and BEATLE-II.

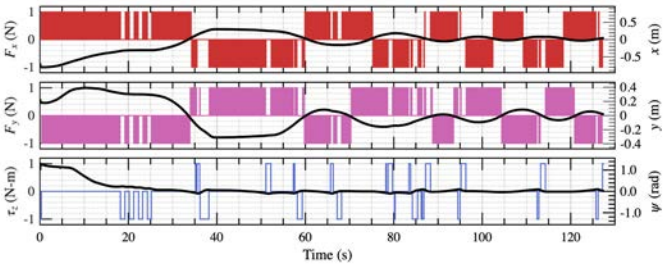

Fig. 7: Closed-loop control performance of BEATLE-I

IV. Experimental Validation

To verify the behaviour of the constructed epoxy floor, a static drift test is used to confirm that the platforms remains stationary within 0.1 mm in x-axis, 0.3 mm in y-axis, and 0.15 deg in yaw over 5 minutes as shown in Fig. 8, indicating sufficient surface flatness and bearing performance. Moreover, the Qualisys MCS offers real-time data at 100 Hz a tracking accuracy of ≈ 0.1 mm in $x - y$ and ≈ 0.05 deg in yaw after calibration.

To further validate the operational capabilities of the facility, an experiment is conducted which implements a PWM-based

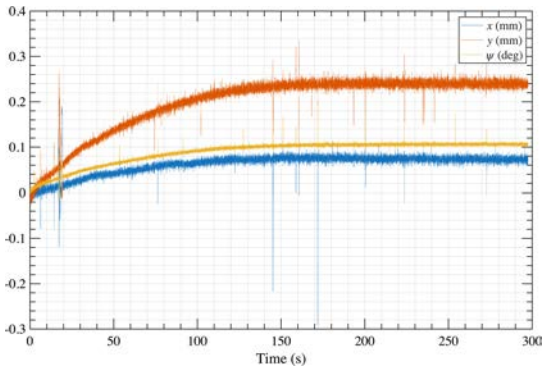

Fig. 8: Drift Test Results for BEATLE-1 on ZeroG Astro Lab Epoxy Floor

on-off control algorithm using feedback from the Qualisys MCS using the reflective markers installed on the top layer of the platform. The controller is designed and implemented on the ground station PC, which sends commands to the platform using real-time telemetry. These commands are received by the low-level controller Arduino GIGA which then commands the respective thrusters via the relay board. The control algorithm is designed to prioritise the control for yaw, and if the yaw error is within the defined bounds of 0.08 rad, then it alternates between x and y axes. The output of the thruster is at a fixed pressure, so the blowing force is constant. However, the duration of nozzle firing is determined by a PID controller. The output of this PID controller is used to define the duty cycle of the PWM signal using a square-wave generator which commands the on-off signal as well as the firing duration for each thruster. In this way, a PWM-based on-off control method is implemented as shown in Fig. **??**, and used to validate the functionality of all the lab resources. Both the ground-station controller and the low-level computer onboard operate at a frequency of 10 Hz. BEATLE-I is commanded to return to the origin $(x, y, \psi) = (0\text{ m}, 0\text{ m}, 0\text{ rad})$ of the calibrated floor space from an initial position of $(x, y, \psi)_{(t=0)} = (-1\text{ m}, 0.5\text{ m}, 1\text{ rad})$. After approximately 130 s, the error converges to within 10 cm for the $(x-y)$ axes and 0.08 rad for the yaw axis. Figure 7 presents the state and actuation trends, which show that when the platform deviates from the set point, thrusters fire in the opposite direction, confirming closed-loop responsiveness. In general, this experiment highlights the proper functioning of the constructed platform and facility. The experiment is conducted multiple times from different starting positions to confirm the repeatability of the lab capabilities.

V. Conclusion

In this article, the University of Liverpool's Zero-G Astro-Lab facility is presented including the design driver, metrology measurements of the epoxy floor, manufacturing of mock terrain and the design of the BEATLE platforms. The experiments highlights the proper validation of the floor and functioning of the platform. Future work will include finishing the construction of BEATLE-II and the implementation of advanced GNC techniques enabled by the modular design of the platform architecture, with a focus on planetary mission operations.

Acknowledgment

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