ABSTRACT

This paper describes the design, creation and verification of a 45 m² air bearing facility at ESTEC, specifically targeted at orbital robotics, named ORBIT (Orbital Robotics test Bench for Integrated Technology). The facility consists of a 5 x 9 m epoxy floor with stringent flatness requirements and various support infrastructure. A set of fourteen VICON motion tracking cameras enable position tracking of moving objects in the facility. A pressurised air installation is part of the facility which provides a filtered, pressure- and flow regulated air outlet. We also describe the air bearing platforms used to provide free floating capability for the test objects. We conclude this paper with the results of tests which have been performed to verify the facility.

1 INTRODUCTION

Over the past years the subjects of combined orbital robotics and advanced guidance, navigation, and control (GNC) have become increasingly important for European space missions. Automated docking has been successfully carried out and attention is now being focused on the capture of uncooperative targets for Active Debris Removal in the framework of Clean Space initiative. Additionally, the two subjects are capital for missions (underway and in preparation) for landing and sampling on low-gravity bodies such as comets, asteroids and small moons.

To support the existing and upcoming missions (such as e.Deorbit [3]) and R&D activities [9, 7, 6, 8] in these high-visibility, technological fields, the Automation and Robotics (A&R) laboratory at the European Space Research and Technology Centre (ESTEC) has been upgraded to include an orbital robotics and GNC facility. This facility supports a large flat floor on which several air-bearing platforms support the activities.

1.1 Ground-based Simulation of Microgravity

Different methods have been developed over the years to emulate micro-gravity on the ground.

Some are less suitable for simulating dynamics of space robots than the others. The most accurate micro-gravity reproduction is a free fall in an evacuated (vacuum) drop tower such as ZARM in Bremen, however micro-gravity is only available for a very short time (4.74 s in the case of ZARM). A slightly longer test can be achieved on a parabolic flight, such as those operated by Novespace, where reasonable micro-gravity can be obtained for durations around 20 seconds. To further extend the duration, water is commonly used. By submerging astronauts or equipment in water together with buoyancy control devices one can extend micro-gravity even further. However, in addition to the capital and operational expense of neutral buoyancy pools, the experiments suffer high drag forces which makes contact dynamics and control more difficult to test for.

Air-bearing facilities have been used since the beginning of spaceflight for such purposes [4]. Air bearings use compressed air to create a thin air cushion between two surfaces and in this way minimise friction. Planar air-bearing facilities consist of an extremely flat surface on which a platform with a platform floats on air bearings fueled by bottled compressed air. Such a facility provides three degrees of freedom, two translational and one rotational.

This paper describes the recent development of such a facility at the the Orbital Robotics and GNC laboratory at ESTEC [1, 2].

2 ORBIT

2.1 Design Drivers

Two main design drives were identified prior to commissioning the installation of the flat floor.

- **Size:** The size of the floor had to be large to be able to cope with large payload structures for an extended amount of time. Especially during spacecraft-spacecraft interaction, which happens in Active Debris Removal (ADR) scenarios, the objects under test need to have sufficient space to simulate the synchronisation and free-drifting phases.
- **Flatness:** The strongest requirement came from the flatness specifications. A not perfectly flat floor leads to drift of the test objects due to gravitational force. Hence, general and local inclinations on the floor needed to be minimised. On a microscopic scale, the
surface finish of the floor had to provide the necessary smoothness to allow the use of air bearing pucks.

2.2 Floor Installation

The multi-layer floor was installed in a step-by-step procedure with various verification steps to monitor the progress and to detect inaccuracies before the next layer of material was applied.

As a first step, the rough concrete surface was ground and cleaned. Then, thin rows made of leveling concrete were applied on the floor. The height of these rows was adjusted to be perfectly leveled with respect to gravity. The level was verified with a Leica AT402 absolute laser tracker. Next, the areas in between the rows were filled with leveling concrete. After another verification with the laser tracker, the first layer of epoxy was applied. The composition of the epoxy was adjusted by the supplier, enabling a lower viscosity to increase the leveling capability. However, lowering it too much resulted in exothermic reactions that caused bubbles to form on the surface. As a result to the material change, the drying time increased to a couple of days and after several attempts, a surface with almost no bubbles was achieved. After another measurement, a few areas were adjusted with fine sandpaper and another layer of thin epoxy was applied. The bubble crates were carefully ground and a final verification measurement was performed.

![Figure 1: Steps of the flat floor creation](image)

2.3 Floor Characterisation

To verify the compliance of the floor to requirements, a characterisation of the floor flatness was done using a Leica AT402 absolute laser tracker, which can be used to measure deviations along the gravity vector to fractions of a millimeter.

As mentioned in the previous chapter, the characterisation was done after each step of the floor installation, as well as at commissioning. It was also repeated 6 months later to check for potential small movements of the building (ORBIT is not on the ground floor). The commissioning characterisation can be seen in figure 2 and shows a maximum deviation of 0.7 mm across the whole surface. But more importantly, it shows no general trend for the floor to tilt in one way or another, something that would have dramatically disturbed any experiment. The measurements performed 6 months later showed no apparent change.

Another parameter to characterise was the local surface roughness. The air bearings used by some of the platforms operate with air-gaps of just a few tens of microns. It is imperative that the roughness is below that level to avoid the air-bearings coming in contact with the floor at any time. A PCE-1200 RT roughness tester was used to measure the roughness values of RA <0.9 µm, RQ <0.6 µm, RZ <1.8 µm [1] and to show that the floor complies at all measured points.

![Figure 2: Lab floor topology map. Heights are along the gravity vector in mm](image)

2.4 Testbed Overview

An overview of the ORBIT facility is displayed in figure 3. Three rows of 45 mm Bosch-Rexroth aluminium profiles are mounted horizontally to the walls which surround the floor (the height from the floor to the lower edge of the profiles is 55 ± 1 cm, 140 ± 1 cm and 225 ± 1 cm). The aluminium profiles are used to mount additional hardware (Planetary terrain mock-ups, cameras, etc.). A set of twelve Vicon motion tracking cameras have been installed on the top row of the profiles. The floor itself is accessible from the higher computer floor of the laboratory by a ramp. The ramp can be folded away in order to use the whole floor for experiments. Heavy items, like the air bearing platforms, can be lifted from the computer floor to the flat floor area through the use of a semi-automatic jib crane. The crane has a maximum lifting capacity of 250 kg. The laboratory in which the facility is embedded has two fully equipped workbenches for mechanical and electrical work as well as a minimum stock of electronic and mechanical components. Additionally, IT workstations are available in laboratory.
2.4.1 Motion Tracking System

A Vicon motion tracking system is used to track the position of objects on the floor. It consists of 12 Vicon Bonita B10 cameras capable of operating at rates of up to 250 Hz as well as an associated switch and computer. The cameras, hardware and Tracker software allows sub-millimeter real-time localisation (up to the framerate of the cameras). The system operates by tracking small reflective balls. A minimum set of four of such markers need to be attached to the test object to fully define a local coordinate system. The markers are seen by the cameras and the Vicon Tracker software calculates their respective position through triangulation.

2.4.2 Pressurised Gas Installation

A pressurised gas installation has been installed in the laboratory in order to supply the air bearing platforms. The installation consists of three parts

- A Bauer Oceanus E scuba dive air compressor for filling on-board gas cylinders with oil- and water free air. It can fill bottles with air up to 200 or 300 bar with a delivery rate of 140 l/min.
- A continuous air supply, provided by an Atlas Copco Scroll SF11 oil-free compressor with built-in dryer. The compressor provides a regulated output of up to 10 bar and a flow of 900 l/min. Together with a large buffer tank, it was installed in the plant room servicing the laboratory, and connected with large-diameter (28) copper pipe to the laboratory where a total of four outlets are installed. Two outlets pressure regulated (up to 8 bar each), and two have flow monitors attached together with a manually operated needle-valve.
- A pressurised nitrogen outlet for cleaning and filling gas thrusters used on the satellite mockups. The outlet is connected to a nitrogen tank on the outside of the building with a copper pipe.

2.4.3 Mass properties testing devices

Two devices have been developed to characterise the mass properties of the air bearing platforms and their respective test objects.

- The Centre Of Gravity (CoG) measuring device consists of three load cells connected to a honeycomb plate with a diameter of 900 mm. The weight and the centre of gravity of objects placed on top of the honeycomb plate are measured and calculated. It can measure weights up to 150 kg with an accuracy of 10g, and determine the CoG position with sub-millimeter accuracy.
- The Moment of Inertia (MOI) measurement device makes use of the flat floor and the air bearing platforms. The air bearing platform is placed on the floor and connected by a set of springs to the aluminum
profiles. The set of springs allows the air bearing platform to oscillate around its axis of symmetry. A gyroscope on the platform measures the frequency of the oscillation which is used to calculate the MOI with an accuracy of around 1-2% depending on the object. Additional objects can be placed on the platforms and as the stack is measured, the MOI of the individual objects can be calculated through superposition.

3 AIR BEARING PLATFORMS

3.1 Overview

Three different floating platforms have been developed to operate on the floor and to cover a broad range of test scenarios. All platforms are fully characterised in terms of mass and inertia and feature a common interface to attach test objects. The common interface is a quadrangular M6 hole pattern (50 mm grid) in which the central hole aligns with the axis of symmetry of the platform.

3.2 Rootless

![Figure 5: Rootless air bearing platform](image)

ROOTLESS (Robotic Testbed for Floating-Dynamics Simulation) is a robotic testbed with constant air supply. This novel platform, developed in-house, allows testing of very light payloads (e.g. cubesats) and for arbitrarily long durations since the mass and inertia of the support air bearing platform is decoupled from the payload. This means that the platform can be supplied by the continuous air supply without disturbing the motion of the payload. It operates using a small Kuka Youbot holonomic robot on which the pneumatics are installed and which is equipped with three air-bearing pucks that are facing upwards. The interface plate, on which the payload is mounted, is floating above these pucks. As the interface plate drifts, its relative motion to the Youbot is detected. Using this information, the Youbot moves to keep itself aligned underneath the centre of the interface plate. By adjusting the height of the air-bearings, the system has the potential to auto-calibrate on an uneven floor and to introduce an artificial gravitational force.

The interface plate for mounting hardware has a mass of 2.944 kg and a calculated MOI of 0.059 kg/m² with respect to axis of symmetry in z-direction. These values can be decreased further by using a specifically designed interface plate for the test object. The maximum payload capacity of the platform is estimated to be around 15 kg. The distance from the floor the top of the interface plate is 295 mm. A detailed description of the system can be found in [5].

3.3 Mantis

![Figure 6: Mantis air bearing platform with a test probe attached and Vicon reflective markers placed around the top plate](image)

MANTIS (Maneuverable Testbed for In-orbit Simulation) is a platform that uses three carbon air bearing pucks and has dedicated air cylinders on-board to operate independent from external air supply. Additionally, eight thrusters are connected to an on-board controller. Figure 7 gives an overview of the pneumatic system. Clean air (compliant with ISO 8573.1) is filled into the cylinders using the Bauer Oceaneus air compressor. A pressure gauge connected to the tanks indicates the current filling status and a relief valve ensures that the maximum tank pressure is not exceeded. Two systems are connected to the air tanks through a needle valve. The first system connects the thrusters to the air tanks. Here, a set of two pressure regulators reduces the tank pressure to a few bars.
Two pressure regulators are used to minimise the influence of the supply pressure effect (SPE). The reduced pressure line is connected to eight solenoid valves which work as thrusters. The second system provides air to the air bearing pucks. The primary pressure regulator is connected through a particle filter and a manual on/off valve to a secondary pressure regulator in which the desired pressure for the air bearings is selected. A buffer tank is used to minimise instabilities in the air supply. Additionally, a solenoid valve is installed which provides an emergency stop function.

![Figure 7: Overview of the pneumatic system of Mantis](image)

The platform is equipped with a BeagleBone Black Microcomputer which interfaces a tank pressure transducer, an IMU, the eight thrusters and the solenoid valve. The computer is connected to the laboratory network through wifi and is powered by battery. Telemetry is received and control of the platform is done through software on an external computer.

Mantis has a dry mass of 25.82 ± 0.05 kg and a MOI of 1.667 ± 0.09 kg/m² around the axis of symmetry in z-direction. If the tanks are filled with air to 150 bar, the mass changes to 27.55 ± 0.01 kg and the MOI to 1.630 ± 0.09 kg/m² around the axis of symmetry in z-direction. The maximum payload capacity for this platform is estimated to be 50 kg. The distance from the floor the top of the interface plate is 320 mm.

3.4 Acrobat

ACROBAT (Air Cushion Robotic platform) is a floating platform that uses four air cushions and has a constant air supply from the pneumatic installation. The mass of this platform is significantly higher than MANTIS and ROOTLESS and can be increased even more by adding weights to dedicated mounting interfaces. The four mounting interfaces for additional weights consist of 30 mm x 100 mm poles which allow the mounting of standard gym-type weights with a maximum diameter of 200 mm. Additionally, a horizontal beam is available to add weights with an offset to the platform COG. This beam is used to adjust the position of the CoG when asymmetrical payloads are placed on the platform.

Acrobat has a mass of 128.85 ± 0.05 kg and an MOI of 8.154 ± 0.09 kg/m² around the axis of symmetry in z-direction. The maximum weight and hence the payload capacity of this platform comes from the maximum load that can be applied to the floor for stability reasons and the lifting capability of the jib crane. The maximum floor capacity is 500 kg/m², the jib crane can carry 250 kg. The distance from the floor the top of the interface plate is 490 mm.

4 EXPERIMENTAL VERIFICATION

Besides the reproduction of immediate contact scenarios, the evolution of the free-drifting trajectory of the air bearing platforms after contact is of interest. The facility was extensively tested in the scope of a cross-validation activity performed in cooperation with GMV [2]. The following paragraph shows the contact experiments that have been performed at the flat floor facility for evaluation the free-drifting trajectory of the Mantis air bearing platform.

4.1 Experiment Setup

A Mitsubishi PA10 robotic arm was statically placed on the flat floor for the experiments. A spherical probe was attached with a 1-DoF compliance device to the tip of the robotic arm. The compliance device, consisting of a set of springs, allowed a defined deformation in one element and protection of the robotic arm from the high loads of a rigid impact. The Mantis air bearing platform was placed stationary in front of the robotic arm. A cylindri-
cally shaped part was attached to Mantis with its axis of symmetry aligned with the axis of symmetry of the platform. During the experiment, the robotic arm approached Mantis with a constant speed and the sphere hit the cylindrical part which resulted in a free drifting motion of the platform. The robotic arm as well as the position of Mantis were tracked at all times through the Vicon motion tracking system. A schematic view of the experiment can be seen in 9.

![Figure 9: Experiment setup, side view](image)

4.2 Experiment Results

Multiple experiments with a range of different approach velocities have been conducted with the velocity vector of the platform being monitored before and after contact (Figure 10). The nominal velocity vector was calculated using the immediate state of motion after contact and extrapolated using a 1-DoF contact model.

The graphs illustrate the platform drift with minimal disturbance for a significant time. A ten percent difference to the nominal value occurs after 4.9 s in the case of 30 mm/s, 6.9 s in case of 50 mm/s and 11.4 s in case of 100 mm/s approach velocity. These disturbances are due to the local imperfections of the flatness of the floor on the sub-millimeter level. While at higher velocities this effect is barely visible, it becomes more significant in lower velocity regimes or for longer durations.

5 CONCLUSION

We described the establishment of a large flat floor air bearing facility at the Automation and Robotics section of the European Space Research and Technology Centre. The floor is supported by three air bearing platforms that allow experiments over a broad range of test scenarios representative for orbital robotics. Additional infrastructure has been installed and commissioned to enhance prototyping capability and to lower the time to experiment.

The facility is a unique and powerful tool for researching contact dynamics or GNC in a micro-gravity like scenario. The convenience of performing tests in a short amount of time and with limited use of manpower has shown the huge potential of the facility. Tests and collaboration have been conducted and initiated with indus-

![Figure 10: Mantis velocity vector change after approach with various velocities](image)
trial partners and national agencies to support technology research and development activities.

6 Acknowledgement

We would like to thank Simon Whyss Uhlmann for developing the the mass properties characterisation devices.

References


