A ROBOTIC TESTBED FOR LOW-GRAVITY SIMULATION

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ABSTRACT

This paper proposes a novel testbed for testing in a microgravity-like environment. We describe the development of a prototype platform based on an omnidirectional mobile robot. When compared to conventional air-bearing facilities, the platform allows experiments with significantly lower inertia. We performed verification tests simulating contact between a chaser and a target in free-floating environment. We have demonstrated accurate dynamics after impact at velocities ranging from $20\,\mathrm{mm\,s^{-1}}$ to $200\,\mathrm{mm\,s^{-1}}$ with payload mass of 4.7 kg and support mass of only 2.9 kg.

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 upcoming missions 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 [2], and R&D activities [5, 6, 7, 12] 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 with several air-bearing platforms.

We start this paper with a short review of ground based microgravity simulation in Section 1. Section 2 illustrates the principle of the proposed testbed and describes the robotic platform in detail. Section 3 describes the experiments. Our experience and possible improvements are discussed in Section 4.

1.1 Ground-based Simulation of Microgravity

Different methods have been developed over the years to emulate microgravity on the ground.

Some are less suitable for simulating dynamics of space robots than the others. The most accurate microgravity reproduction is a free fall in an evacuated drop tower such as ZARM in Bremen, but microgravity is only available for a very short time (4.74 s in the case of ZARM). A slightly longer test can be achieved in a parabolic flight, such as those operated by Novespace, where reasonable micro-gravity can be obtained for a duration of around 20 s. 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 capital and operational expense of neutral buoyancy pools, the experiments suffer high drag forces which make contact dynamics and control tests infeasible.

Air-bearing facilities have been used since the beginning of spaceflight for such purposes [11]. Air bearings use compressed air to create a thin air cushion between two surfaces and in this way minimise friction. Planar air-bearing facilities include extremely flat surface on which a platform with compressed-air container floats using the air bearings. It provides three degrees of freedom; two in translation and one in rotation. A large such facility was constructed as part of the Orbital Robotics and GNC laboratory in 2015 at ESTEC [8, 9].

Spherical air bearings provide low torque in attitude and have been extensively used for attitude control tests. Spherical and planar air bearings can be combined to provide up to 5 degrees of freedom.

A more recent development are facilities which use industrial robotic arms commanded by a physical model of a floating object [1]. External interactions can be simulated using feedback control. These robotic arm facilities usually allow simulation of all 6 degrees of freedom. However, purely robotic facilities rely on the credibility of the introduced physical model and the performance of the hardware.

1.2 From Flat Surface to a Mobile Robot

Air bearing facilities have several downsides.

Firstly, the object under test (hereafter referred to as *payload*) must be mounted on an air-bearing platform. This platform has to have its own air and energy supply in order not to suffer forces and torques from the connected air hoses and electrical cables. As such the duration of the experiments is limited by the energy and air storage.

Secondly, by placing the payload on such a platform, the inertia of the platform combines with that of the payload.

And thirdly, the flat surface is limiting the maximum distance the platforms can operate over. Installing and maintaining a permanent flat surface for experiments is expensive and may be impractical for universities and smaller research facilities.

This paper proposes a novel air-bearing robot that overcomes all these three limitations.

2 ROBOTIC TESTBED

The robotic testbed, based on KUKA Youbot mobile robot and named *Robotic Testbed for Floating-Dynamics Simulation (ROOTLESS)*, allows to decouple the payload from the platform, run experiments for extended durations, and is scalable to do tests in larger areas.

We use air bearings to provide a low-friction movement in the horizontal plane similar to conventional air-bearing facilities. Three air bearings are mounted on a mobile robot pointing upwards. The payload is mounted on a flat plate that floats on a thin air film on top of the air bearings. As the payload moves the mobile robot follows respectively using the relative-position information from a contactless sensor.

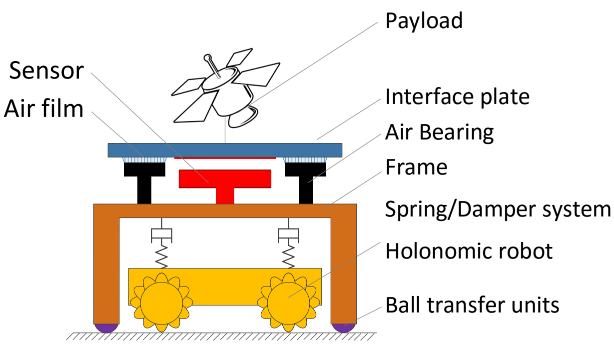

Figure 1: System overview.

2.1 System Overview

The proposed platform consists of four core subsystems: Locomotion, Pneumatic, Tracking, and Payload. Figure 1 gives an overview of the main hardware elements.

The Kuka Youbot is a commercially-available holonomic mobile robot widely used by academic researchers [3]. Figure 2 shows the robot. We opted for an existing solution to benefit from the community, to shorten the development time, and to lower the price.

The Youbot is equipped with an onboard Linux computer. We chose the Robotic Operating System (ROS) as robotic middleware for the software development since the drivers for the platform itself already existed. We added a Beaglebone Black microcomputer which processes data from the position sensor.

2.2 Locomotion

The core requirement for our application was unconstrained planar locomotion. The Kuka Youbot is equipped with mecanum wheels so the robot can move in any direction from any configuration.

Figure 2: Youbot from Kuka. It provides unconstrained planar movement with use of mecanum wheels.

Mecanum wheels feature series of rollers mounted at 45° angle around its circumference. By rotating each wheel with different computed velocity one can move in any direction. The maximum velocity in the forward direction of the robot is $0.8\,\mathrm{m\,s^{-1}}$.

2.2.1 Vibration Damping

The drawback of mecanum wheels is the discontinuous point of contact with the ground. There is a gap between each roller and as the wheel rotates the rollers collide with the ground. This motion introduces significant vertical vibrations to the robot and disturbs the motion of the payload.

The vibrations are intolerable for the application and hence we added a damping element. In order to damp the vibrations, we built a frame around the Youbot which carries the air bearings and the payload. The weight of the frame and payload is supported by ball transfer units which allow holonomic movement with small rolling resistance. Vertical vibrations from the robot are damped by a spring-damper system between the frame and the robot. This proved to be sufficient to minimise the vertical vibrations.

2.3 Pneumatic System

The pneumatic system provides a continuous and stable flow of air to the air bearings to provide frictionless movement of the payload. The platform has a standard quick coupling to connect oil- and water-free pressurised air. The air is routed through a manual on/off switch and a particle filter. Next, a pressure regulator with a connected buffer tank is attached to Youbot to provide a constant pressure to the air bearings. The tubing from the regulator to the air bearings is of equal length to avoid different pressure levels. The main components of the pneumatic system are the three carbon air-bearing pucks. These air bearings have a porous carbon surface through which the air flows evenly and provide a steady air gap (Figure 3).

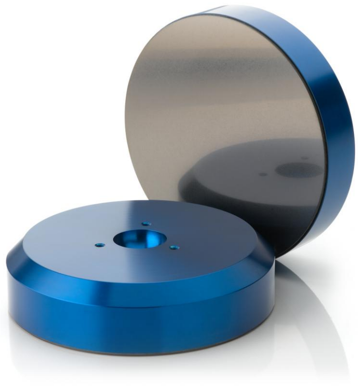

Figure 3: New Way air bearings.

2.4 Payload

The air gap between the air bearings and the payload is only a few micrometers wide. Therefore it is crucial that the interface surface between the payload and the air bearings is flat and smooth, or else the surfaces could come in contact. Additionally, the flat material must be stiff, so as not to deform when a heavier payload is used. The material should also be light, so as not to constrain the minimum mass of the whole payload.

We tested several interface materials: aluminum, acrylic, and glass. Glass, while being delicate to handle, has the best floating properties. For the purpose of interface material we used an off-the-shelf circular mirror with a diameter of 50 cm and a thickness of 5 mm.

We attached the mirror to a 10 mm-thick honeycomb panel with equidistant M6 inserts to provide a generic and easy to use mounting interface for the payloads. The total weight of the interface plate is 2.94 kg.

The interface plate is the only addition to the payload. Because the interface plate is symmetrical it is easy to include it in simulation models. Unlike bulky platforms with pneumatic systems in conventional air-bearing facilities, it does not introduce any uncertainty in the model. To reduce the weight even further, a dedicated interface plate for the payload which only consists of the smooth surface can be used.

2.5 Tracking

The mobile robot moves by tracking the position of the floating payload relative to the platform and by keeping itself aligned with the center of the interface plate. A PID controller commands the movement of the mobile robot.

2.5.1 Robot Control

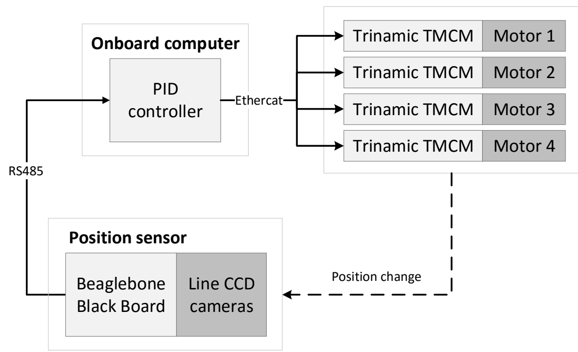

Figure 4: Relative position control loop.

Figure 4 shows the feedback loop for the relative position control. The interface plate is circular so only translation degrees of freedom, i.e. x and y position, are measured and controlled. The relative position is measured by a custom-built contactless sensor especially designed for this purpose; see Section 2.5.2 for details. The raw data from the sensor are processed by a Beaglebone Black microcomputer. The Beaglebone Black Board feeds the position information to the onboard computer through RS485. The feedback loop is closed through a PID controller running on the onboard computer and commands the velocity vector of the platform.

The velocity-vector commands for the Youbot are then converted into angular-velocity commands for each motor. The four independent motors are controlled by Trinamic TMCM motor controllers which are connected with the onboard computer via Ethercat.

2.5.2 Position Sensor

We built a custom contactless vison-based sensor to measure velocity and position of the payload relative to the center of the mobile robot. It is composed of an active and passive part. The active part is located on the mobile robot; there are three parallel rows of line-scan cameras and LED backlights (Figure 5). The passive part is a full black circle printed on a bright background on the interface plate.

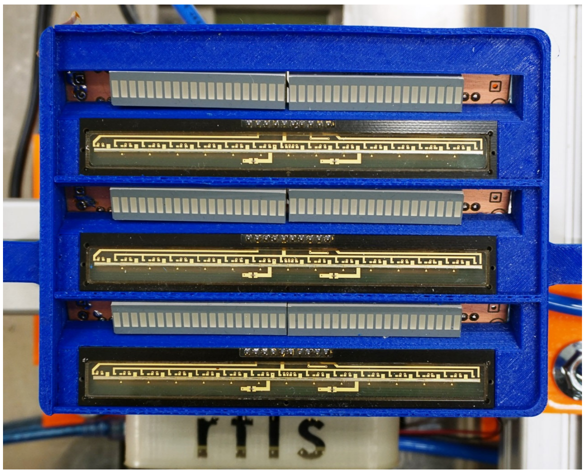

Figure 5: Custom sensor for measuring the relative position between the payload and Youbot.

The gap between the sensor and the target is small enough that the camera readings are not perturbed by ambient light. The analog reading of each pixel is compared in hardware to a threshold so the edges of the circle can be read directly by the microcomputer. The detection of two edges of the circle is sufficient to estimate the position of the center of the target as long as the radius of the circle is known.

This sensor provides the absolute position of the centre of the interface plate relative to the centre of the mobile robot with a resolution better than 0.5 mm and at a rate of 2 kHz. It works over distance up to 20 cm, does not need calibration, and only requires a passive target painted on the payload.

2.5.3 Safety and Operation

An operator can control the platform remotely. The operator can start and stop the tracking of the payload and teleoperate the robot.

For safety, we added two Hokuyo laser scanners which detect the distance from the robot to his surroundings. This is especially useful if, during an experiment, an unexpected object is detected in close proximity of the platform. In such a scenario the feedback control is shutdown and the robot is stopped.

Additionally, we mounted bumpers to prevent the interface plate and the payload from sliding off the air-bearing support when tracking is stopped.

2.6 System Integration

Figure 6 shows the final version of the prototype. Rapid prototyping technologies, such as 3D printing, were used for mechanical integration of the system. The pneumatic system is mounted directly to the robot while the air bearings and position sensor are mounted to the damped frame. The honeycomb panel and interface plate, on which a payload can be mounted, can be seen on top.

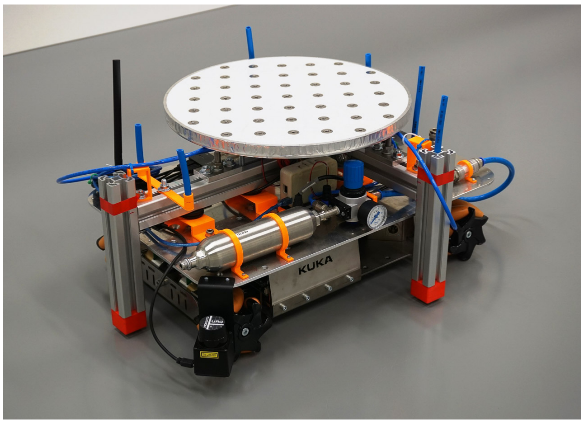

Figure 6: Final prototype of ROOTLESS.

3 EXPERIMENTAL VALIDATION

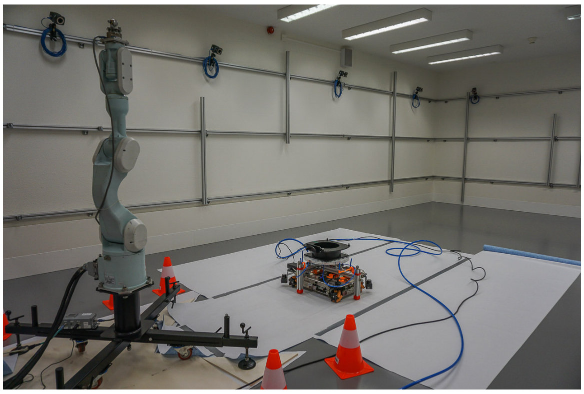

Figure 7: Setup of the experiments carried out on the ORBIT flat-floor facility with Vicon motion capture system. On the left can be seen Mitsubishi PA10 robotic arm used to impact the payload and in the center ROOTLESS with a mockup of a satellite launch adapter ring as payload.

3.1 Experiment Setup

To verify the system, we used very simple and predictable contact experiments. For this we placed a known compliance device, a spring-damper system, in the contact loop. The interface of the contact was designed as a sphere to closely emulate a single-point contact (Figure 8). Additionally a load cell measured forces and torques.

We performed the experiments on the ORBIT flat-floor facility instrumented with a VICON motion tracking system. The objects were tracked with a frequency of 250 Hz with sub-millimetre precision. We placed a protective foil on the floor to prevent damage to the floor from

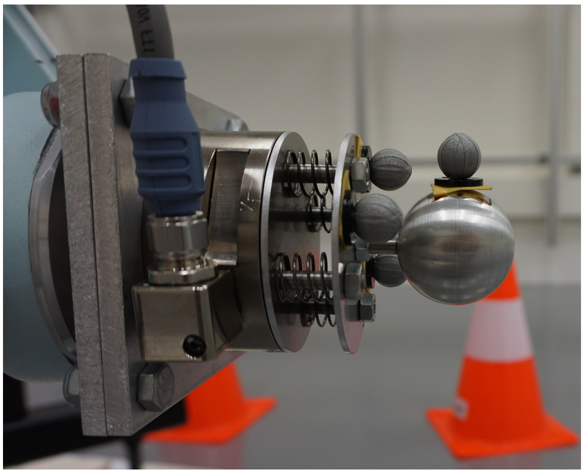

Figure 8: The robotic arm end effector used in the experiments. From left: load cell, compliance device, contact interface. Spherical targets are attached for VICON motion capture.

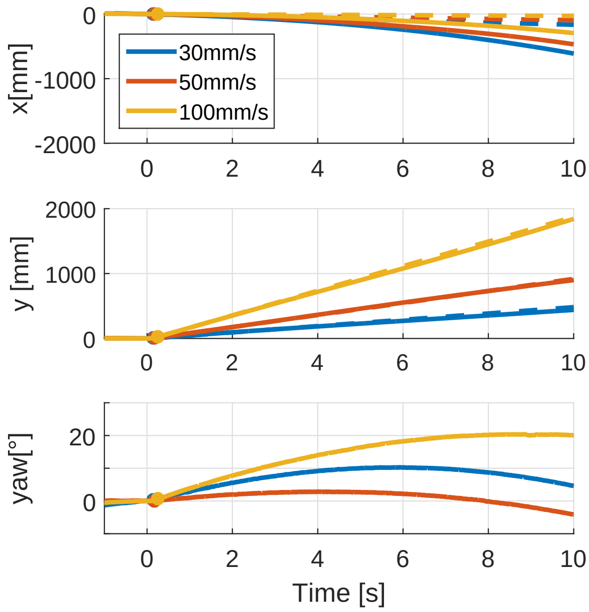

Figure 9: Position evolution comparison after contact with different approach velocities in y direction. The dashed line shows the expected trajectory after contact without any external disturbance.

the wheel rollers. Figure 7 shows the setup of the experiments.

A Mitsubishi PA10 robotic arm was used to achieve repeatable and accurate contact. We commanded the linear trajectory of the arm along the y dimension to approach a satellite mockup with known parameters free floating on ROOTLESS.

The experiments were performed as part of the cross validation of the ORBIT flat-floor facility with PLATFORM-ART, developed by GMV. A more detailed description of the experiments can be found in [10].

3.2 Experiment Results

We performed impacts with relative velocities of $10\,\mathrm{mm\,s^{-1}}$, $30\,\mathrm{mm\,s^{-1}}$, $50\,\mathrm{mm\,s^{-1}}$, and $100\,\mathrm{mm\,s^{-1}}$. We repeated each experiment with different relative velocity four times. Figure 9 displays the sample position evolution of free-floating satellite during the experiment for each velocity except $10\,\mathrm{mm\,s^{-1}}$.

For the lowest velocities, the external disturbances, caused mainly by the imperfect inclination of the floating plane, were dominant.

Higher velocities were limited by the maximum velocity of Youbot and by the reaction delay caused by the feedback loop.

The error in the y direction (the direction of push) is below 10 % over a distance of 2 m. Figure 10 shows the error between the expected and measured position of the payload for multiple experiments for an approach velocity of $50\,\mathrm{mm\,s^{-1}}$. In the x direction, the error is persistent between the experiments and can be explained by a constant force caused mainly by the inclination of the floating plane.

We identified the force in the x direction by fitting the measured error data with a parabola:

$$\dot{x} = \frac{a}{2}t^2 + v_0 t + x_0$$

where t is the time, a the acceleration, x_0 the initial position, and v_0 the initial velocity. The fitted curve is shown in Figure 10: the estimated acceleration from the four experiments was $7.24\,\mathrm{mm\,s^{-2}}$. The acceleration corresponds to an inclination of 0.042°.

Figure 11 compares the position of the payload and the robot during the initial phase of the contact experiment with approach velocity of $50\,\mathrm{mm\,s^{-1}}$. It shows how the feedback controller tracks the floating payload. One can notice reaction delay to the initial movement of the payload of approximately 0.25 s. After 0.7 s the robot reaches the velocity of the payload. The errors, like slipping of the wheels, are corrected by the feedback controller, which results in oscillations along the trajectory of the robot. The reaction time, the acceleration of the robot, and the oscillations in position do not affect the motion of the payload illustrating the advantage of this system.

4 CONCLUSION

We have demonstrated a novel testbed for free-floating dynamics in two dimensions. We have shown that it can reproduce the dynamics during and after impact

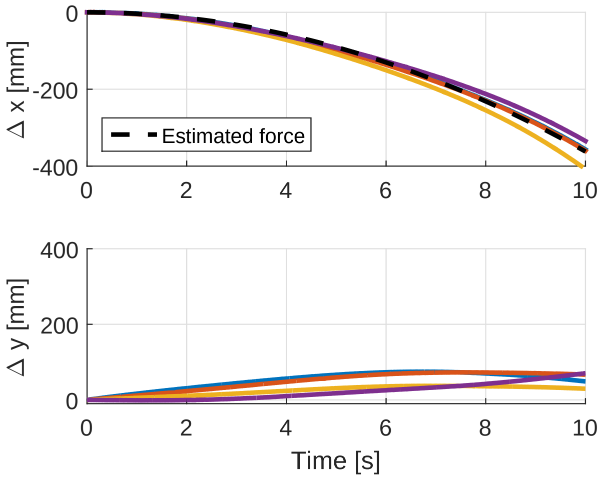

Figure 10: Error between expected position and real position after floating payload release for repeated contact experiments with approach velocity $50\,\mathrm{mm\,s^{-1}}$. *The dashed line shows estimated constant force caused by inclination of the floating plane.*

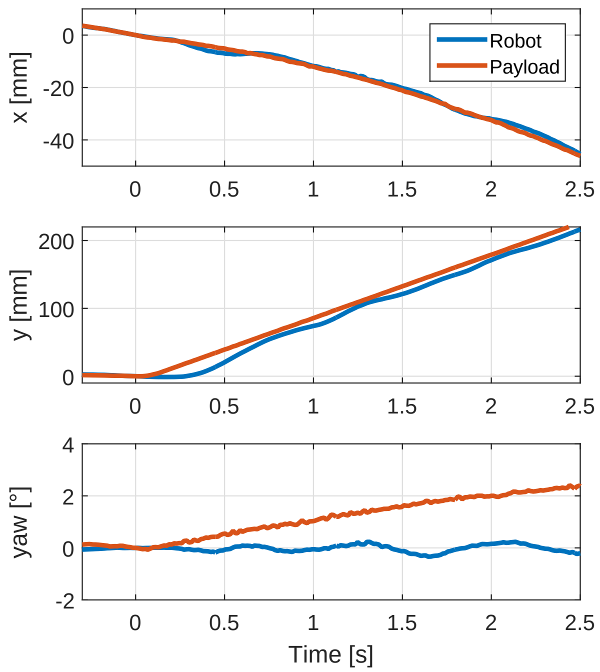

Figure 11: Position evolution of payload and robot during simple contact experiment with approach velocity $50\,\mathrm{mm\,s^{-1}}$. *Time of contact between the chaser and the payload was at* $t_c = 0\,\mathrm{s}$.

accurately down to very low masses. Moreover we have shown that it is possible to do this while decoupling the air-bearing platform from the payload thereby offering in practice unlimited experiment duration and an operating area that is limited only by the length of your air supply hose.

In the experiments we have demonstrated accurate dynamics after impact at velocities ranging from $20\,\mathrm{mm\,s^{-1}}$ to $200\,\mathrm{mm\,s^{-1}}$, but the upper limit can be increased by further optimisation of the controller and the distance between the air bearings.

The main limitation was the parasitic acceleration introduced by the inclination of the floating plane caused by the unevenness of the floor and height misalignment of the air bearings. In our tests we measured parasitic acceleration to be below $8\,\mathrm{mm\,s^{-2}}$.

The mass of the interface plate was only 2.94 kg but it can be lowered by designing specific interface plate for the experiment.

4.1 Future Work

The most important future update will be the implementation of automatic levelling of the horizontal plane. The inherent inclination due to an uneven floor and the misalignment of the air bearings are the main limitations of the platform. Using feedback control we will adjust the height of the air bearings to compensate these effects.

Moreover, it is possible to introduce artificial gravity by slightly tilting the horizontal floating plane. The capability to simulate low-gravity situations will be unique compared to other facilities, and allow for the validation of robotic systems on asteroids, comets and small moons.

The mechanical design could be further simplified by replacing the current mecanum wheels with omnidirectional wheels specially designed to minimise the gap between the rollers. It would allow to remove the frame with ball transfer units. For instance [4] proposes such wheel design.

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