REACSA: ACTUATED FLOATING PLATFORM FOR ORBITAL ROBOTIC CONCEPT TESTING AND CONTROL SOFTWARE DEVELOPMENT

Willem Suter, Gunter Just, and Marti Vilella

Orbital Robotics Laboratory (ORL), European Space Agency (ESA), ESTEC, Noordwijk, Netherlands,
gunter.just@esa.int, marti.vilella@esa.int

ABSTRACT

This paper aims to introduce REcap-ACrobat-SAtsim (REACSA), a new actuated and controllable floating platform developed in ESA's Orbital Robotics Laboratory (ORL). The platform is composed of three individual stacks that recreate the behaviour of a satellite's Attitude and Orbit Control System (AOCS) within a two-dimensional plane. With an actuated platform such as REACSA, an interaction scenario between two free-floating bodies can be set up in order to investigate contact dynamics in space or to study other related research fields such as in-orbit servicing, rendezvous and docking, or active debris removal. The REACSA platform also provides a great testbed for the development of advanced control algorithms.

Keywords: space robotics; orbital robotics; testbed; control; ESA.

1. INTRODUCTION

As the demand for space applications continues to increase drastically, both industry and academia have been relentlessly working towards the conception and development of more complex, more numerous, and increasingly larger space infrastructure. Such a steep increase has resulted in an urgent need for the development and operation of facilities worldwide, capable of testing various mission or technology concepts, analysing their designs, and supporting their flight qualification. For this specific purpose, the European Space Agency (ESA) constructed their own free-floating satellite simulator/flat floor facility named ORBIT (Orbital Robotics Bench for Integrated Technology) in 2015 [9], which is capable of hosting a series of air-bearing-based robotic platforms with a variety of different payloads. The original intent of the ORBIT facility was to provide an environment capable of simulating realistic free-floating contact dynamics for the testing of full-scale space hardware [10]. Over the past few years, two large floating platforms were designed and built in order to accommodate a wide range of payloads of various masses, shapes, and functions [22]. Several test campaigns were organised within the facility so far, such as testing of the SpaceBok locomotion system in simulated microgravity in 2018 [14] or, more recently, testing of the ClearSpace-1 capture system in 2022 [7]. Since then, the ORL team, in charge of maintaining and operating the ESA facility, has been working on the development of controllers capable of actively controlling one of the floating platforms in order to provide a wider and more repeatable set of testing scenarios. The newly controlled platform, REACSA, has been intentionally designed with high mass in order to simulate larger satellites and can, therefore, also support large payloads. With the mass ratio between payload and satellite being more realistic, concepts do not require as much downscaling, which in turn provides a better analysis of their primary functions and mechanical design. REACSA has additionally been integrated into a standardised software architecture with sensor and actuator data being transmitted in a common format at fixed and reliable rates. This provides a simple and effective solution for integration of third party algorithms, time synchronised data, and the test of hardware-in-the-loop concepts. A graphical user interface for test operators has been created to provide a means of tracking the progress of ongoing tests. Finally, a simulation of the ORBIT facility and the REACSA platform has been created with the intent to develop and test designs prior to a campaign on the physical floor. The simulation environment along with the software architecture has already successfully enabled the development of two controllers capable of manoeuvring REACSA along predefined trajectories.

2. STATE OF THE ART

As far back as the 1960s, the international space community began the development of satellite simulator testbeds in order to better understand, and qualify, satellite AOCSs. Since then, dozens of universities, research centres, and space agencies have joined the effort to research and test a wider variety of topics spanning from Active Debris Removal (ADR) to cooperative satellite manoeuvres and formation flying. The developed testbeds are tailored to test specific scenarios and assemblies, which is highly dependent on the testbed's configuration and size, as well as on the amount of platforms available and their level of actuation.

For the purpose of categorising the testbeds encountered in literature, a distinction has been made based on the amount and type of the Degrees of Freedom (DoF) that can be simulated. The most common testbeds can generate negligible friction in 3-DoFs (planar and attitude motion or purely attitude motion), with some having a fixed base for their floating platforms as their main interest is in control and dynamics of satellite manipulator systems for in-orbit operations. Other more advanced facilities can simulate 5-DoFs, such as the 5-DoF Spacecraft Simulator for Autonomous Rendezvous and Docking (SSARD) at the Georgia Institute of Technology (US) [6], while the most advanced laboratories, such as the ADAMUS 6-DoF spacecraft simulator at the Rensselaer Polytechnic Institute (US) [20], can simulate all 6-DoFs and thus provide an almost perfect microgravity experience for the test subjects. In order to operate large floating platforms, laboratories mostly accommodate floor-based test facilities made out of poured epoxy or slabs of granite. These testbeds, often referred to as flat floors, can reach sizes of up to 630 m^2, such as the Air Bearing Floor (ABF) in NASA's Johnson Space Center (US) [13], and are primarily used to test the contact dynamics of space hardware or the AOCS of flight models.

For performing research on much smaller cubesats and nanosatellites, as well as testing manoeuvres and controllers, laboratories have favoured table-based testbeds made from a single slab of granite or a large glass plate. These tables have the added advantage that they can be tilted to simulate low-g body conditions for testing robot locomotion systems or landing gear systems. A thorough review of past and present facilities, including the research they enable and a detailed description of some of the air-bearing based platforms they operate, can be found in Rybus, 2016 [15].

New facilities continue to emerge around the world as more specialised and higher fidelity testbeds are required to pursue cutting-edge research. In 2020, the University of Bologna (IT) inaugurated a 3-DoF dynamic testbed for nanosatellite attitude verification [12]. In 2022, the Nanjing University of Aeronautics and Astronautics (CH) released a publication detailing the characterisation of their new air-bearing testbed used to simulate spacecraft dynamics and control [8]. Also in 2022, the Zero-G lab in Luxembourg constructed a 3 x 5 m epoxy floor in order to emulate active debris removal scenarios [11]. This new facility has, in addition to a floating platform, a rail-mounted controllable robotic arm for hardware-in-the-loop testing.

Additional floating platforms have also recently been designed, such as the new Platform Integrating Navigation and Orbital Control Capabilities Hosting Intelligence Onboard (PINOCCHIO) of the La Sapienza University of Rome (IT), which was developed in order to research the attitude control of very large and flexible satellites [17]. In 2021, the Luleå University of Technology in Sweden created Slider, a small controllable floating platform that is meant to be used by researchers for spacecraft proximity operations [2]. Even more recently, in 2023, York University (UK) constructed two floating platforms in order to simulate rendezvous and docking scenarios using a robotic arm and vision-based pose estimation on the chaser platform, and a capture fixture on the target platform [18]. Additionally, current space research contin-

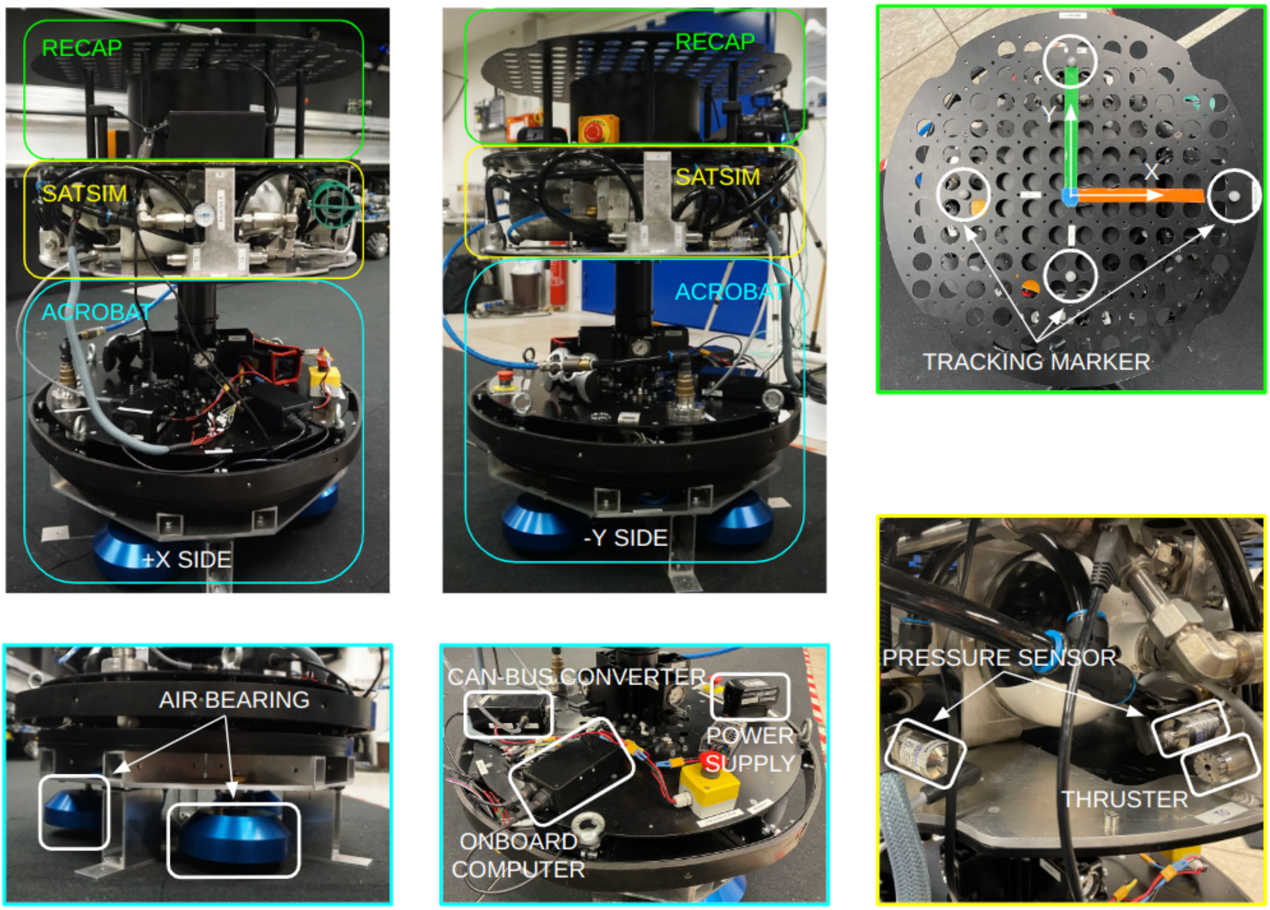


Figure 1. An overview of REACSA, an actuated floating platform consisting of three stacks: ACROBAT (blue), SATSIM (yellow) and RECAP (green).

ues to take place in many facilities worldwide with a notable focus on collision-free path planning for cooperative satellites [16], pose tracking control for spacecraft proximity operations [1], and autonomous capture and detumbling of non-cooperative satellites using manipulator arms [19].

3. REACSA AIR BEARING PLATFORM

3.1. System overview

REACSA is a cylindrical platform of 0.7 m diameter and 1 m height. It is composed of three individual stacks that, when combined, recreate the behaviour of a three degree of freedom satellite Attitude and Orbit Control System (AOCS), operating within a two-dimensional plane.

ACROBAT (Air Cushion ROBotic plATform), the bottom stack (seen in the blue box in Figure 1), achieves negligible friction with the ground by creating a stable air gap between its three air bearings and the flat floor facility (ORBIT) of the ORL. The three New Way 20 cm air bearings generate a 5 micrometer air gap capable of carrying a load of up to 800 kg each. ACROBAT also hosts an onboard computer that runs the drivers for the sensors and actuators of the system, namely: the pressure sensors, thrusters, reaction wheel, and air bearings. Additionally, it contains a custom CAN bus converter that is used to communicate with the pressure sensors and the reaction wheel. Finally, a removable 18V Makita battery is used to power all the onboard electronics as well as to provide power to the solenoid valves that operate the thruster's open or close states.

SATSIM (SATellite SIMulator), the middle stack (seen in the yellow box in Figure 1), houses a set of eight compressed air thrusters that can apply discrete planar forces and torques to the platform. This central platform also contains a set of two litre, 300 bar, air tanks that provide constant 8 bar pressure to the thrusters and 6.5 bar pressure to the air bearings via three stages of pressure regulators. To increase the stability of the pressure for the thrusters, a 0.5 litre buffer tank has been installed upstream of the thrusters bank inlets. In order to supply the air bearings directly and simultaneously increase the pressure stability in the thrusters, it is possible to connect the air bearings directly to a constant pressure source via a tether. It is also possible to tether both the thrusters and the air bearings. REACSA can therefore be operated in both a tethered and a untethered configurations, with the tethered configuration inducing small disturbances to the platform, but allowing for infinite experimentation time.

RECAP (REaction Control Autonomy Platform), the top stack (seen in the green box in Figure 1), contains a single reaction wheel that can apply continuous torque to the platform by spinning a 4 kg cylindrical mass with a moment of inertia of 0.047 kgm^2. The reaction wheel and its Nanotex controller are also powered via a removable 18 V Makita battery. On top of RECAP, four reflective tracking markers have been placed in order for the VICON Motion Capture (MoCap) system to track REACSA within the ORBIT facility.

Together, these stacks are representative of the inertia of a satellite through their combined weight of roughly 200 kg and can accommodate additional payloads of up to 50 kg. The principal properties of REACSA can be found in Table 1. The platform's Centre of Gravity (CoG) is roughly centred on the platform's central axis, with a maximum deviation of 1.5 cm without payload. The vertical position of the CoG has not been identified so far. A dynamics model of the platform can be found in Anton 2022 [5]. For safety purposes during operations on the floor, the maximum velocity is limited to 1 m/s, while the rotational velocity is limited to 30 deg/s. REACSA has variable autonomy depending on how much thruster firing is being commanded and whether the system is tethered or untethered. With full tanks and without any firing, the platform can free-float for roughly 35 minutes and indefinitely when tethered. However, most experiments in the laboratory have demonstrated that actively controlling the platform reduces tests duration to between 5 and 10 minutes when untethered and to between 7 and 14 minutes when the air bearings are tethered (but not the thrusters).

Table 1. REACSA stack and reaction wheel (RW) properties (mass, moment of inertia (MoI), and major dimensions). These values are measured without air in the tanks, which can add a maximum of 1.5 kg to SATSIM.

Stack	Mass [kg]	MoI [kgm^2]	Height [m]	Diameter [m]
ACROBAT	147.55	10.09	0.619	0.7
SATSIM	37.63	1.416	0.201	0.7
RECAP	13.62	0.67	0.296	0.7
RW	4.01	0.047	0.05	0.26
REACSA	202.81	12.223	1.116	0.35

3.2. Onboard sensors and actuators

Thrusters: In order to provide thrust to the platform, REACSA is equipped with four pairs of counter-facing, radially aligned, solenoid valve controlled thrusters. These are independently operated and provide constant thrust for a maximum duration of 0.3 s and a minimum duration of 0.1 s when operating at 7 bar, which generates a nominal force of 10.36 N [4]. However, the amount of thrust depends linearly on the operating pressure of the thruster's firing banks, and as such, it can be varied as required to any value between 8 and 14 N. Between firings, the thrusters require a downtime of 0.2 seconds in order for the pressure to rebuild. When multiple thrusters are fired at once, the force can drop by up to 1 N.

Reaction wheel: To provide fine rotational control to the platform, REACSA is equipped with a single reaction wheel mounted co-axially on the central axis of the platform. The reaction wheel is controlled with a commercial off-the-shelf (COTS) controller that provides both closed-loop proportional integral (PI) based torque and velocity control. The wheel is operated within a 500 rpm window and can apply a maximum theoretical torque of 1.44 Nm for 1.7 seconds.

VICON motion capture system: In order to track the platform's position and orientation, the ORBIT facility is equipped with a set of 16 VICON motion capture cameras capable of tracking a set of four infrared markers mounted on top of REACSA. The VICON tracker software provides the pose of the platform at an update frequency of up to 250 Hz with sub-millimetre position accuracy.

Pressure sensors: Digital pressure sensors have been incorporated into the system to track the pressure within the tanks, at the inlets of the thruster firing banks, and at the inlets of the air bearings. Tracking the pressure in the tanks allows operators to know when a test needs to be concluded, while tracking the pressure in the thruster banks gives insight into how nominal the thruster force is during firings (constant pressure provides constant force within the optimal operational time window). Tracking the pressure at the inlets of the air bearings allows the operators to guarantee that the platform will not loose levitation during an experiment. All pressure levels can be monitored remotely from the operator station.

ORBITcam ceiling camera: A Raspberry Pi High Quality camera named ORBITcam has been mounted on the ceiling above the ORBIT facility in order for operators to record images or videos of their experiments in real-time. The camera is equipped with a fish-eye lens, allowing for a wide field-of-view covering the entire floor area. The camera intrinsic parameters have been computed for three sets of resolutions (HD, HD+, and Full HD), therefore, the images can be undistorted during post-processing or used by object tracking or pose estimation algorithms in real-time.

4. FACILITY

4.1. ORBIT flat floor facility

The ORBIT flat floor is a 4.75 m wide by 8.78 m long epoxy floor, which at the time of writing, has a maximum height deviation of 1.8 mm and a maximum floor induced acceleration of 0.02 m/s^2 and an average acceleration of 0.0035 m/s^2. To determine the floor's height deviation and overall flatness, elevation measurements made in a 10 by 18 grid pattern on the floor were recorded using a high precision laser tracker with a maximum permissible distance error of 69 μm. These measurements were also used to create a heightmap of the floor with a 19.5 mm/px resolution by performing a cubic interpolation of the available data as can be seen in Figure 2. The induced acceleration values were determined by following the same process described in Tsiotras 2014 [21]. This heightmap was then turned into an extremely fine mesh by using the open-source software Blender. In order for all position data to be referenced to a common origin, the flat floor has been fitted with a set of near-infrared LED markers that have been calibrated in such a way that the origin of the MoCap coordinate system can be made to coincide to within 2 mm of the actual floor's physical centre. This setup allows for a repeatable reference frame to be used between experiments and allows for the floor's mesh coordinates to be referenced with respect to

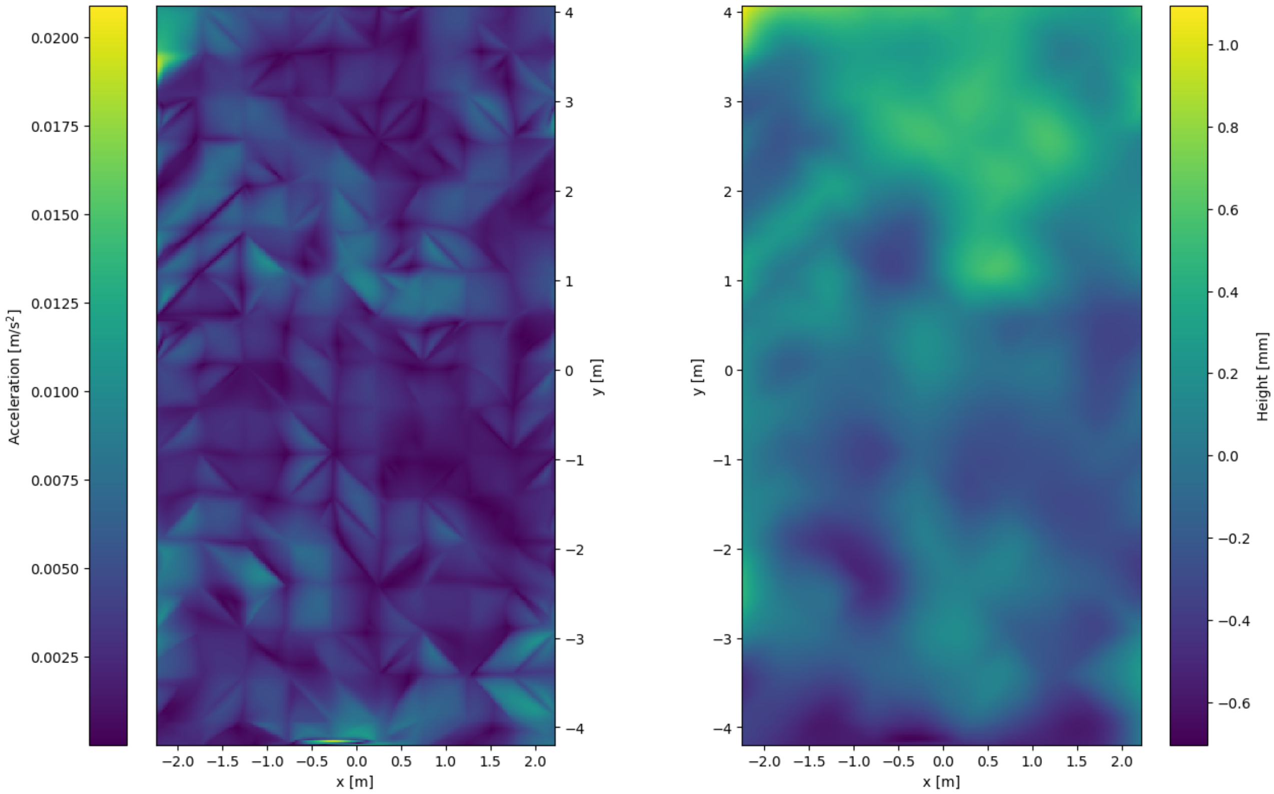


Figure 2. ORBIT flat floor induced acceleration (left) and height map (right) interpolated based on high precision laser tracker measurements. The height map serves as the basis for the creation of an extremely fine mesh replica of the flat floor used in the simulation environment of the ORBIT facility [2].

---

[2] The heightmaps shown in Figure 2 are based on measurements made in 2023. The multicolor heightmaps seen in the other figures of this paper are based on measurements made in 2015.

the physical floor. Tests between simulation and the physical floor can therefore be compared and the knowledge of the floor's elevation or induced acceleration can be integrated into potential disturbance cancelling or trajectory following algorithms.

4.2. Operator station

As can be seen in Figure 3, an operator station has been fitted next to the flat floor in order to remotely operate REACSA and supervise ongoing tests within the ORBIT facility. The operator station is also conveniently located next to the platform's stowing stand, air compressor, and the lifting crane used to deploy REACSA onto the flat floor and pick it back up.

5. SIMULATION ENVIRONMENT

A Gazebo-based robot model and simulation environment have been created with the purpose of emulating the dynamic model of the platform and of the flat floor. REACSA has been simplified to a set of three statically linked bodies, which masses, shapes, and moments of inertia are representative of the physical stacks. The air bearings have been modelled as three individual cylinders. Zero friction and a soft contact has been imposed between the virtual air bearings and the floor to simulate the frictionless air gap generated by the real-world bearings and to allow for a smoother interaction between the floor's jagged mesh and the modelled air bearing rims. The thrusters have also been modelled as eight individual cylinders fixed to the SATSIM model on which forces can be applied to recreate the effect of firing a thruster. Finally, the reaction wheel has been modelled as a cylinder connected to the RECAP model by a continuous rotational joint. The cylinder has been given the same physical properties as the real reaction wheel, and torques can be applied to the joint linking it to the remainder of the platform in order to recreate the effect of spinning the wheel up and down and therefore changing the moment of inertia of the entire system. The ORBIT flat floor mesh makes up the floor of the simulation environment with the addition of four surrounding walls to mimic the ORBIT facility and keep the system enclosed. Screenshots of the simulation environment and REACSA model can be seen in Figure 3. The simulation has been extensively tested to ensure that the free-floating dynamics of the simulated platform correspond well to those of the physical system. However, the simulation environment has its limitations due to inaccuracies in the models and the flat floor mesh interpolation, as well as the numerical errors generated by the physics engine while trying to solve the rigid body dynamics between the discrete mesh and the modelled air bearings. These flaws can induce unexpected forces that would not appear with the real system, which is why the simulator is primarily used to develop new controllers and safely test concepts prior to carrying out trials on the delicate floor. Additionally, Gazebo with the ODE

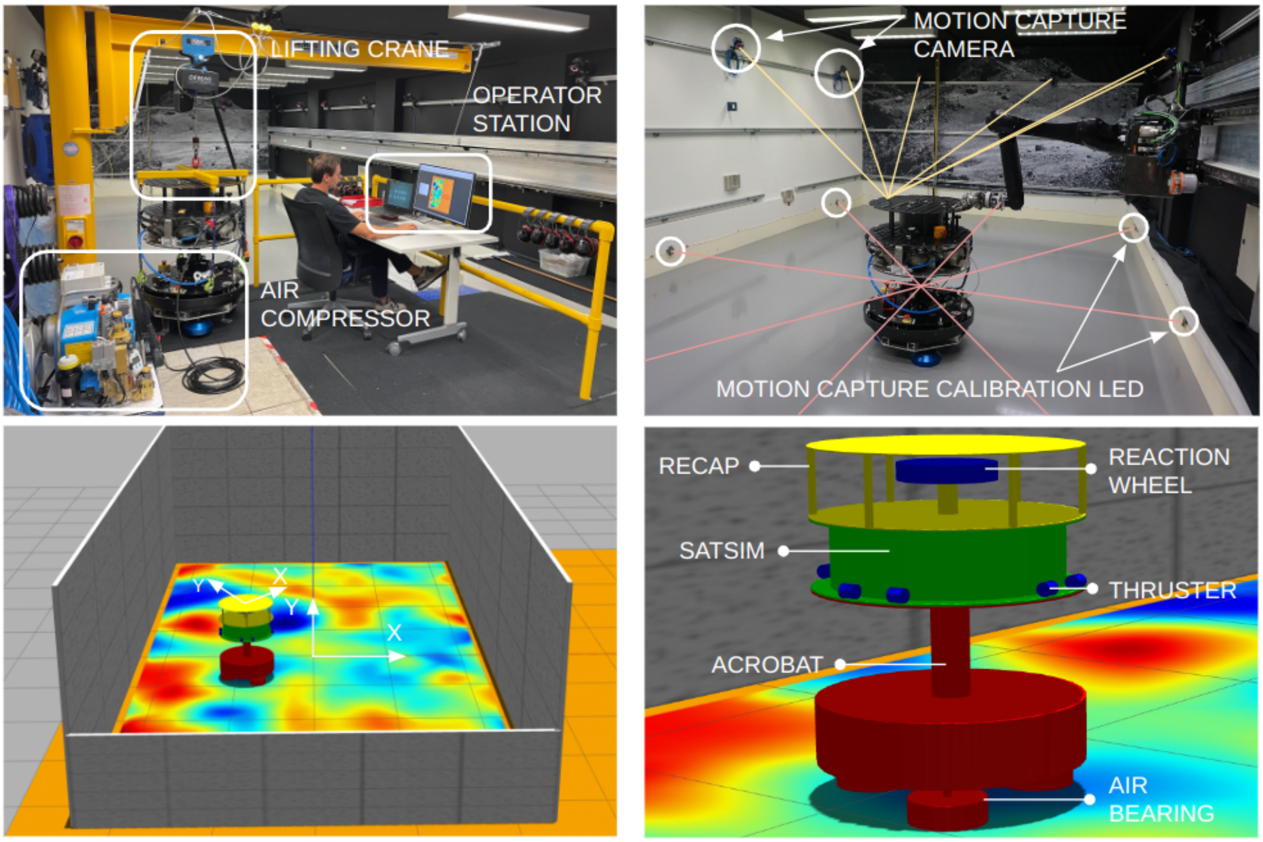


Figure 3. An overview of the operator station (top left) and ORBIT flat floor with the MoCap cameras and calibration LEDs (top right). Screenshots of the Gazebo simulation environment containing the ORBIT flat floor mesh (bottom left) and a simplified model of REACSA (bottom right).

physics engine has been proven to have a nondeterministic behaviour when it comes to solving complicated contact dynamics. The authors of this paper hope to address this issue in the future and to use the simulation environment for the benchmarking of free-floating platform controllers.

6. CONTROLLER DEVELOPMENT AND TESTING

6.1. Software architecture to operate REACSA

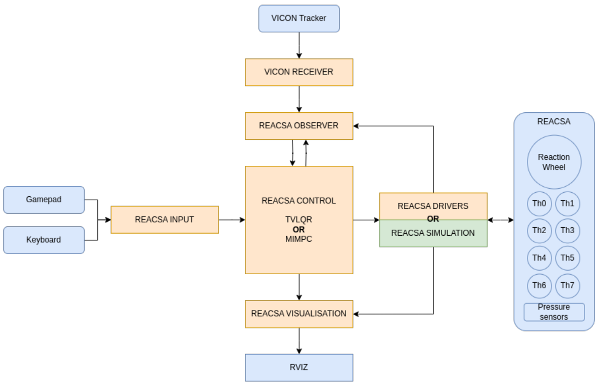


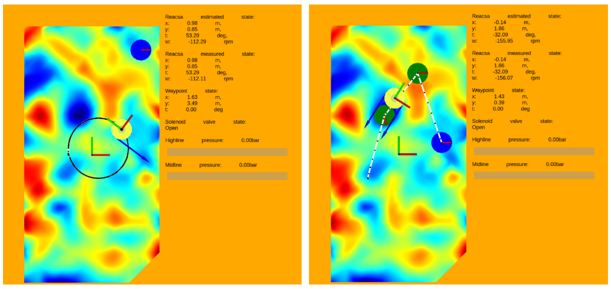
Figure 4. An overview of the REACSA ROS 2 package-based software architecture. Via a keyboard or gamepad, an operator can send an action request to the control node. The control node makes use of the observed state, which filters in data coming from both, the system drivers, and the VICON tracker, to compute the actuation commands. These commands are sent on the network and received by the drivers, which then apply the corresponding actuation to the system. When the system is being simulated, the system drivers are replaced by plugins that interact with the physics engine simulating the REACSA system and the flat floor.

A multitude of ROS 2 packages have been created with the intent to facilitate the development of controllers and other related algorithms for controlling REACSA both in simulation and on the physical floor. Together, these packages contain a set of nodes that communicate over the ROS 2 network. The packages are functionally split between packages containing the physical actuator and sensor drivers, the simulation environment, the controllers, the state observers, the operator keyboard and gamepad command inputs, the ROS Visualization (RViz) user interface, and the report creation. All packages can be run on separate machines as long as they are connected to the same local network. This allows operators to share computational load across different machines or to run computationally heavy controllers on dedicated hardware. The thruster, reaction wheel, and pressure sensor drivers all run on REACSA's onboard computer and the communication with the controller is achieved via a 5 GHz WiFi link. The controller package has been designed with a base class that provides a standardised method of subscribing to the robot state, publishing controller commands, and executing operator requests. The reaction wheel commands are defined as torques to be executed by the wheel controller, while the thruster commands are defined as binary *on* or *off* states. In velocity mode, the commanded reaction wheel torques are converted into a velocity change by using the equation below:

$$\Delta\omega = \frac{\tau\Delta t}{I} \tag{1}$$

, where τ is the commanded torque in Nm, t is the time delta over which the torque is applied in sec, and I is the wheel's moment of inertia in kgs^2. Equation 1 is a good first order approximation under the assumption that the torque ramp-up time is negligible in comparison to the time delta over which the torque is applied. All controller commands and control loops are currently run at 10 Hz, the state observer is run at 100 Hz, while the sensor and actuator state data is provided at rates between 1 and 100 Hz depending on the hardware. Operators can visually track ongoing simulation or real tests using a customised RViz window as can be seen in Figure 5. With the help of the visualisation, operators can see the current state of the platform, the planned trajectory, as well as the states of the onboard pressure sensors, the thrusters and the reaction wheel. They can also execute trajectories by means of a keyboard or a gamepad, as well as operate the actuators directly, such as firing the thrusters or spinning the reaction wheel up and down. During a test, all the relevant data can be recorded in multiple ready-to-use formats and a test report is auto-generated to facilitate the post-analysis of the experiment. The software architecture has been designed in such a way that the development of controllers and state observers can be done entirely using the simulated environment. The simulator inputs and outputs are identical in format to the ones encountered within the physical system. As such, once a design has been demonstrated to function in simulation, it can be directly tested on the physical hardware with little to no alterations. This plug-and-play concept has drastically sped up the development of new controllers, allowing researchers to focus their attention on the control algorithms rather than on interfacing with the hardware or the simulator. A flowchart of the software architecture workflow can be found in Figure 4.

6.2. Example controllers



```
Reacsa     estimated     state:
x:       0.98       m,
y:       0.85       m,
t:       53.29      deg,
w:       -112.29    rpm

Reacsa     measured      state:
x:       0.98       m,
y:       0.85       m,
t:       53.29      deg,
w:       -112.11    rpm

Waypoint     state:
x:       1.63       m,
y:       3.49       m,
t:       0.00       deg

Solenoid     valve     state:
Open

Highline     pressure:     0.00bar

Midline      pressure:     0.00bar
```

```
Reacsa     estimated     state:
x:       -0.14      m,
y:       1.86       m,
t:       -32.09     deg,
w:       -155.95    rpm

Reacsa     measured      state:
x:       -0.14      m,
y:       1.86       m,
t:       -32.09     deg,
w:       -156.07    rpm

Waypoint     state:
x:       1.43       m,
y:       0.39       m,
t:       0.00       deg

Solenoid     valve     state:
Open

Highline     pressure:     0.00bar

Midline      pressure:     0.00bar
```

Figure 5. Screenshot of the RViz window during two simulated trajectory following experiments using the TVLQR controller: waypoint trajectory (left), 1 m radius circle (right).

To date, the ORL has developed two different controllers for the purpose of maintaining a stable position, piloting REACSA along simple trajectories (straight lines, spot turns, circular paths), or to follow a series of static waypoints. The main goal for the development of these controllers is to be able to actively steer the platform along a path with a controlled velocity, allowing for realistic contact dynamics scenarios to be simulated. The controllers have been proven to successfully perform slow fixed-velocity trajectories with translational and rotational velocities as low as 5 cm/s and 1 deg/s. Both controllers have also been proven to be robust against the incorporation of additional payloads up to 40 kg (co-axial positioning), to the execution of tethered operations, and to external force disturbances when maintaining a fixed position. The first controller is a Time Varying Linear Quadratic Regulator (TVLQR) controller, combined with an Interior Point Optimiser (IPOPT) trajectory state planner that converts the computed continuous-force commands into binary thruster commands via a Sigma Delta modulator [3]. The second controller is a Mixed Integer Model Predictive Control (MIMPC) controller with a short prediction horizon that directly commands the thruster states with binary control actions. For both controllers, an Extended Kalman Filter (EKF) is used to fuse the global pose data with the actuator state data in order to predict the full platform state (pose, twist, and reaction wheel velocity). An example of three waypoint following trajectory tests, spelling out the ORL lab's name, which was performed with the MIMPC controller, can be seen in Figure 6.

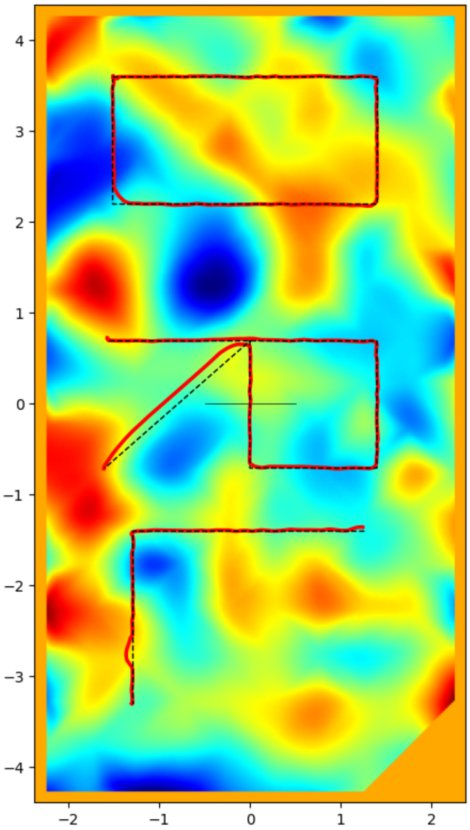


Figure 6. Ground track measurements recorded during an experiment using the MIMPC controller with the physical system. The individual letters were created with the execution of three waypoint trajectories.

7. USE CASES

With the current improvements in the software architecture and the two controllers already developed, REACSA has reached a state of maturity that allows this platform to be used as an active AOCS for the testing of contact scenarios with free-floating payloads. A prominent use case in this area is, for instance, the trajectory control of a chaser that aims to capture a space debris mock-up mounted on another floating platform. Additionally, owing to the pose control precision and robustness of the controllers, REACSA can serve as a testbed to perform more complicated research and qualification tasks, such as testing docking mechanisms for Autonomous Rendezvous and Docking (ARD) operations, satellite relative navigation technologies, control and operation of satellite manipulator systems for complex assembly, servicing, or other tasks.

REACSA is also particularly well suited for research in the field of control theory. The ORL has created a simple and effective infrastructure in order to perform research in control-related fields, such as developing new controllers, adding new sensors for better pose estimation, performing a platform system identification, or integrating the flat floor's height map and associated acceleration map into a control feedback loop.

The laboratory is open to collaborations with both industry as well as academia, implemented through various ESA channels. Interested parties are warmly invited to contact Marti Vilella or Gunter Just to discuss potential applications in more detail. For commercial activities see ESA's technology website[3], and for collaborating in novel research refer to OSIP[4].

REFERENCES

[1] Abin Alex Pothen, Alexander Crain, and Steve Ulrich. Pose tracking control for spacecraft proximity operations using the udwadia–kalaba framework. *Journal of Guidance, Control, and Dynamics*, 45(2):296–309, 2022.

[2] Avijit Banerjee, Jakub Haluska, Sumeet G Satpute, Dariusz Kominiak, and George Nikolakopoulos. Slider: On the design and modeling of a 2d floating satellite platform. *arXiv preprint arXiv:2101.06335*, 2021.

[3] A. Bredenbeck, S. Vyas, M. Zwick, D. Borrmann, M.A. Olivares-Mendez, and A. Nüchter. Trajectory optimization and following for a three degrees of freedom overactuated floating platform. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 4084–4091, 2022.

[4] Anton Bredenbeck. SatSim-REACSA - a floating platform for simulation of micro-gravity with three degrees of freedom. Master's thesis, Julius-Maximilians Universität Würzburg, 2022.

---

[3] `https://technology.esa.int/lab/automation-and-robotics-laboratories`

[4] `https://ideas.esa.int`

[5] Anton Bredenbeck, Shubham Vyas, Martin Zwick, Dorit Borrmann, Miguel Olivares-Mendez, and Andreas Nüchter. Finding and following optimal trajectories for an overactuated floating robotic platform. *arXiv preprint arXiv:2206.03993*, 2022.

[6] Dae-Min Cho, Dongwon Jung, and Panagiotis Tsiotras. A 5-dof experimental platform for autonomous spacecraft rendezvous and docking. *AIAA Infotech at Aerospace Conference and Exhibit and AIAA Unmanned...Unlimited Conference*, 04 2009.

[7] Riccardo Dipietro. CLEARSPACE-1: ESA and the space debris challenge. `https://www.spacevoyaging.com/clearspace-1-esa-and-the-space-debris-challenge`, 2023. Accessed: 11 September 2023.

[8] Zheng Huang, Wei Zhang, Ti Chen, Hao Wen, and Dongping Jin. Characterizing an air-bearing testbed for simulating spacecraft dynamics and control. *Aerospace*, 9(5):246, 2022.

[9] Hendrik Kolvenbach and Kjetil Wormnes. ORBIT - a facility for experiments on free floating contact dynamics. In *13th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), ESTEC, Noordwijk, The netherlands*, 2015.

[10] Hendrik Kolvenbach and Kjetil Wormnes. Recent developments on orbit, a 3-DOF free floating contact dynamics testbed. In *13th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2016)*, volume 6, 2016.

[11] Xiao Li, Maxime Hubert Delisle, Baris Can Yalcin, Carol Martinez Luna, Olga-Orsalia Christidi, Miguel Angel Olivares Mendez, Gonzalo Rodriguez, and James Zheng. Emulating active space debris removal scenarios in zero-g lab. 2022.

[12] Dario Modenini, Anton Bahu, Giacomo Curzi, and Andrea Togni. A dynamic testbed for nanosatellites attitude verification. *Aerospace*, 7(3):31, 2020.

[13] NASA. Jsc engineering: Air bearing floor. `https://www.nasa.gov/centers/johnson/engineering/integrated_environments/air_bearing_floor/index.html`, 2023. Accessed: 11 September 2023.

[14] Nikita Rudin, Hendrik Kolvenbach, Vassilios Tsounis, and Marco Hutter. Cat-like jumping and landing of legged robots in low gravity using deep reinforcement learning. *IEEE Transactions on Robotics*, 38(1):317–328, 2021.

[15] Tomasz Rybus and Karol Seweryn. Planar air-bearing microgravity simulators: Review of applications, existing solutions and design parameters. *Acta Astronautica*, 120:239–259, 2016.

[16] Tomasz Rybus, Mateusz Wojtunik, and Fatina Liliana Basmadji. Optimal collision-free path planning of a free-floating space robot using spline-based trajectories. *Acta Astronautica*, 190:395–408, 2022.

[17] Marco Sabatini, Paolo Gasbarri, and Giovanni B Palmerini. Design, realization and characterization of a free-floating platform for flexible satellite control experiments. *Acta Astronautica*, 2023.

[18] Lucas Santaguida and Zheng H Zhu. Development of air-bearing microgravity testbed for autonomous spacecraft rendezvous and robotic capture control of a free-floating target. *Acta Astronautica*, 203:319–328, 2023.

[19] Lucas Francesco Santaguida. Study of autonomous capture and detumble of non-cooperative target by a free-flying space manipulator using an air-bearing platform. 2020.

[20] Kelsey Saulnier, David Pérez, Grace Tilton, Daniele Gallardo, Chris Shake, R. Huang, and Riccardo Bevilacqua. Operational capabilities of a six degrees of freedom spacecraft simulator. 08 2013.

[21] Panagiotis Tsiotras. ASTROS: A 5DOF experimental facility for research in space proximity operations. *Advances in the Astronautical Sciences*, 151:717–730, 2014.

[22] Martin Zwick, Irene Huertas, Levin Gerdes, and Guillermo Ortega. ORGL - ESA's test facility for approach and contact operations in orbital and planetary environments. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Madrid, Spain*, volume 6, 2018.