A distributed nanosatellite attitude testing laboratory for joint research activities

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Abstract. During the last decades, there has been an increase in the use of satellites of reduced dimensions. Among the others, microsatellites (mass from 11 to 200 kg) and nanosatellites (1 to 10 kg) have been the ones receiving increasing interest from Universities for educational activities [1], [2]. Their reduced cost, complexity and developing time compared to larger satellites make them particularly suitable for student projects. In this regard CubeSats (satellites of standardised dimensions, based on 1 unit, 10x10x10 cm) were developed at Caltech with the goal of having a low cost and fast to be developed satellite [3]. The CubeSat form factor has then been widely used also for scientific and commercial space missions [4]. Alongside the development of nanosatellites, there has been an increase in the need for better CubeSat testing for improving CubeSat reliability [5]. As reported in an extensive study on 855 CubeSats [4], at the year 2018 almost 25% of CubeSats missions failed in their early life stage (*infant mortality*). One of the subsystems more difficult to be tested is the Attitude Determination and Control System (ADCS). This subsystem includes sensors for attitude determination, actuators for attitude control and an onboard controller. Integrated subsystem testing is a challenging task since the device under test should freely rotate under low torque conditions and sensors/actuators should be stimulated. A common way to provide a free rotational environment is to use an air bearing table [6].

The University of Bologna developed its own solution for ADCS testing with a dynamic attitude simulator testbed for nanosatellites [7]. Recently a collaboration between the Microsatellite and Space Microsystem laboratory of the University of Bologna and the STAR laboratory of the Polytechnic University of Turin was established to develop a distributed laboratory for nanosatellite ADCS testing and development. This project enables joint research activities for both research groups in a collaborative framework. The work done included the development of a new Air Bearing Table (ABT) in the Unibo laboratory, the development of a custom ADCS mock-up compliant with the 1U form factor in the Polito laboratory and a joint hardware integration and test campaign.

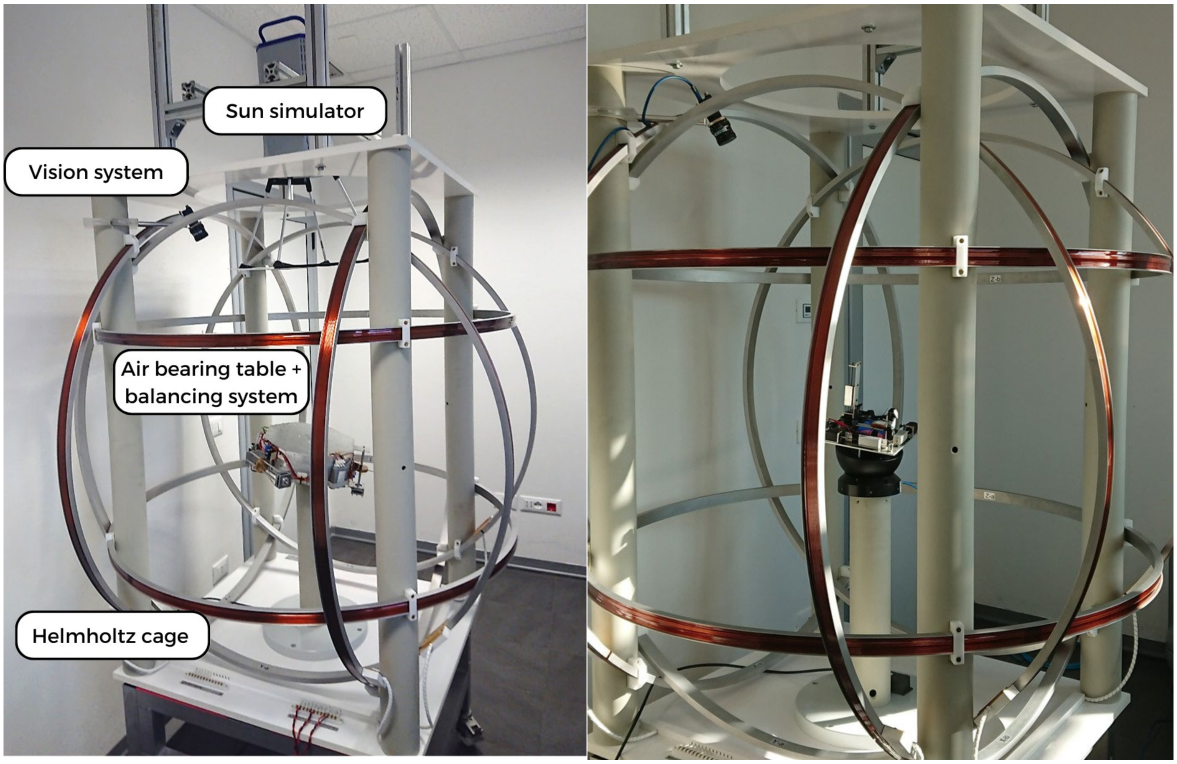

Figure 1: The attitude simulator testbed of the Unibo. The air bearing table for satellites with mass up to 4 kg is shown on the left, the one for satellites with mass up to 1 kg is shown on the right.

The attitude simulator testbed of the University of Bologna integrates several subsystems for the simulation of the Low Earth Orbit (LEO) environment including:

- Air Bearing Table and Automatic Balancing System (ABS) providing three degree of freedom rotational motion in a low torque environment;
- Helmholtz cage for Earth magnetic field simulation;
- Sun simulator;
- Metrology system for ground-truth attitude generation

The facility is described in detail in [7], here its main features are reported. The ABT and ABS are used to reproduce the attitude dynamics of a satellite in space. The external torques acting on a nanosatellite in LEO can be as low as 10^-6 Nm [8]. For ABT facilities, the gravity torque caused by the misalignment between the Centre of Mass (CM) and Centre of Rotation (CR) of the platform is the biggest disturbance torque and needs to be minimised. This can be done by acting on the relative position between CR and CM through a balancing procedure. A coarse balancing can be obtained by evenly distributing the platform components' mass while fine balancing is achieved using sliding masses actuated by stepper motors in an automatic balancing procedure. The fine balancing includes both a part of feedback control and a part of system identification and is described in [9]. The Helmholtz cage is used to reproduce the magnetic field in LEO, where satellites are often equipped with magnetic field sensors and magnetic actuation. A magnetorquer and a closed loop control system are used to accurately track a desired variable magnetic field. The sun sensor consists of a LED lamp able to reproduce the visible part of the Sun emission spectrum. The metrology system consists of a calibrated monocular system. Two ABT have been developed: one for satellites with mass up to 4 kg and the other for satellites with mass up to 1 kg (see Figure 1). The latter has been upgraded to allow the housing of a CubeSat of 1U standard dimension (provided by the Polito) with a dedicated locking mechanism and to host new models of stepper motors.

The facility of Turin has been used for initial basic tests and components implementation in the ADCS mock-up. The PoliTo Clean Room, which is used in the assembly, integration, and functional verification of CubeSats and products that require a controlled environment and special cleanliness, was used in the integration process. The Clean Room is a secluded volume of 60 m^3 and is a 20 m^2, equipped with appropriate equipment. It is suitable for hosting up to three operators while maintaining an ISO7 cleanliness grade. The vertical laminar flow bench is a carefully enclosed cabinet designed to prevent contamination of any particle-sensitive product. Air is drawn through a HEPA filter and blown in a very smooth, laminar flow towards the user. The cabinet is made of stainless steel and other special materials, with no gaps or joints where spores might collect. The equipment is certified for a cleanliness level of ISO5 (Class 100).

Figure 2: Polito clean room present in Turin

Once the interface with bologna had been studied, a preliminary identification of the possible tests that could be carried out using the elements of the facility was made. An initial analysis identified the following testing activities as compliant with the available instrumentation:

1. Verification of the interfaces of the basic board by Electrical Ground Support Equipment (EGSE);
2. Verification of the interfaces of the ADCS board by EGSE;
3. Verification of the correct functioning of the magnetic torquers by means of Helmholtz cage;
4. Verification of attitude maintenance downstream of the test facility's intrinsic disturbances;
5. Verification of correct operation of the magnetometers by comparison with outputs supplied by the IMU;
6. Verification of correct operation of the magnetometers by comparison with outputs supplied by the visual camera;
7. Verification of correct direction of magnetometer dipole actuation;
8. Stabilisation tests downstream of random input around the friction-free axis determined by the air bearing;
9. Verification of the correct operation of the sun sensors using visual camera and sun simulator;

10. Assuming the equatorial plane as the orbital plane, it is possible to test the maintenance of nadir pointing by the actuators of the subsystem, without restrictions on the number of orbits.
11. Once the testing activities were established, the development of the Polito testbed began.

The development process included two main aspects: mechanical interface development and functional board development. For the mechanical interface, a universal and interchangeable locking system was developed to keep the testbed within standardised dimensions for the CubeSat format. Structural integrity was also taken into consideration, along with the weight of the structure, which needed to be as low as possible. For the functional (base) board, a solution was developed for power supply and data exchange with the subsystem (ADCS) board. A board was designed with the required components for power supply, data communication and data processing, including two batteries, a Raspberry PI0-W processor, a hardline connector, ADCs, 5 and 3.3 V regulator circuits, and a 32GB microSD memory. The chosen microprocessor was equipped with a Wi-Fi communication capability, and four types of bus were used for data transmission to the microprocessor. The ADCS board implements two single-axis control laws under test: PD and Y-dot.

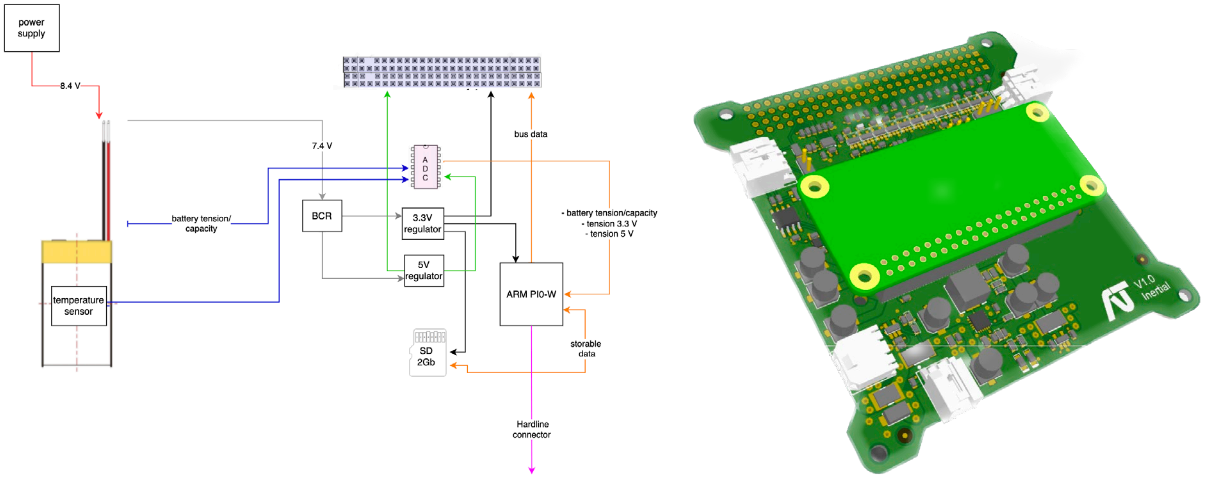

Figure 3: OBC functional board schematic and PCB

Using a CAD software, a 3D model of the mechanical interface was created, which was designed to contain the functional board and the subsystem board and 3D printed in PLA material. A mass mock-up was assembled with the functional and ADCS board models for fine-tuning and verification of correct functioning during balancing procedures in Bologna.

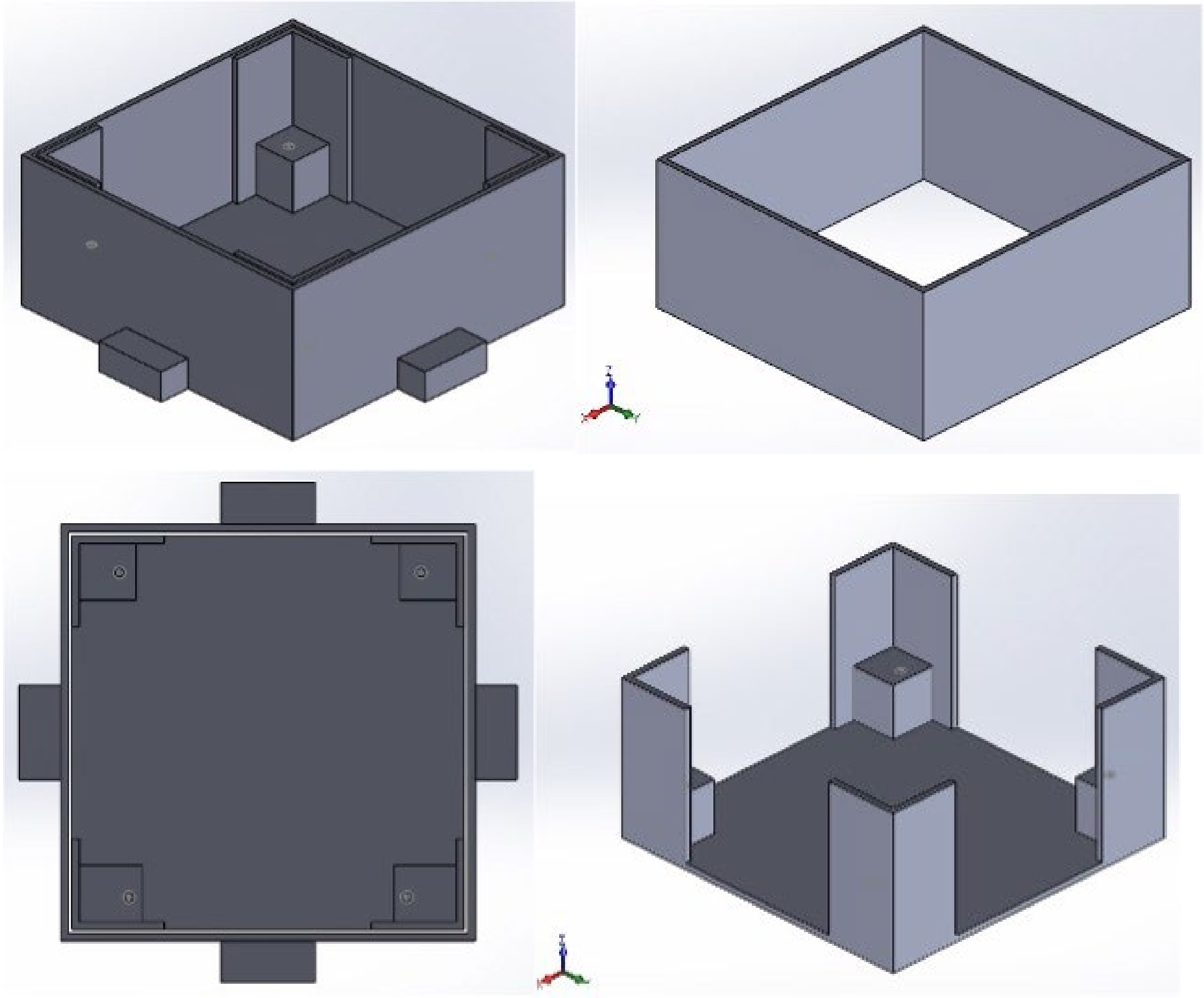

Figure 4: 3D model of the mechanical interface of the mock up

The upgrade on the Unibo facility took into consideration different constrains/requirements:

- Possibility to host and fix a CubeSat with 1U form factor and mass up to 350 g (specifications provided by Polito);
- Minimisation of the disturbance torques with particular attention to the gravity torque;
- Minimisation of the overall mass and dimensions to keep inertia characteristics as similar as possible to the ones of the 1U CubeSat under test;
- Provide hosting for electronic equipment used by the ABS (includes stepper motors, onboard microprocessor, IMU, other electronics and wiring).

The onboard electronics was mainly inherited from the existing platform while new stepper motors with integrated linear guides have been used. The design phase included the exploration of different possibilities for hosting the CubeSat and components and meeting the other requirements. After some iterations between the two teams a solution employing 3D printed L-shaped blocks and pods was adopted as a mechanical interface between the Air Bearing Table and the CubeSat (visible in Figure 5). Although during the realisation of the CAD model we tried to be as accurate as possible, the actual platform differed from the model for some aspects:

- The plate was 2 mm thicker due to limited plate thickness options from the supplier, this resulted in an increase in overall mass;
- The stepper motors and linear guides were 250 g heavier with respect to the mass indicated on the CAD model, this also resulted in an increase in overall mass.

The increase in mass, located mainly above the CR, could have jeopardized the possibility of perform the platform coarse balancing. The problem was solved by putting counterweights inside the air bearing hollow. This solution, although not ideal since it increased the overall mass and inertia, was preferred over others solutions being the most time effective one.

The components integration process involved both Unibo team and Polito team. Prior to the integration, the stepper motors were tested at different motor stepped and acceleration. The goal of the tests was the minimisation of the vibration due to motor resonance. Once all the electronic components have been integrated on the platform, the automatic balancing system was tested. This step required a considerable transfer of information from Unibo to Polito, for this reason documentation explaining in detail the balancing process and best practice has been produced. The test of the automatic balancing system showed that the disturbance torque acting on the new platform after the balancing process is lower than 5x10-5 Nm. Figure 6 shows the results of the tests in terms of residual torque. Solutions for further improving this result are under study today. An experimental campaign to test the Polito CubeSat Attitude Control System is foreseen for the period of March 2023.

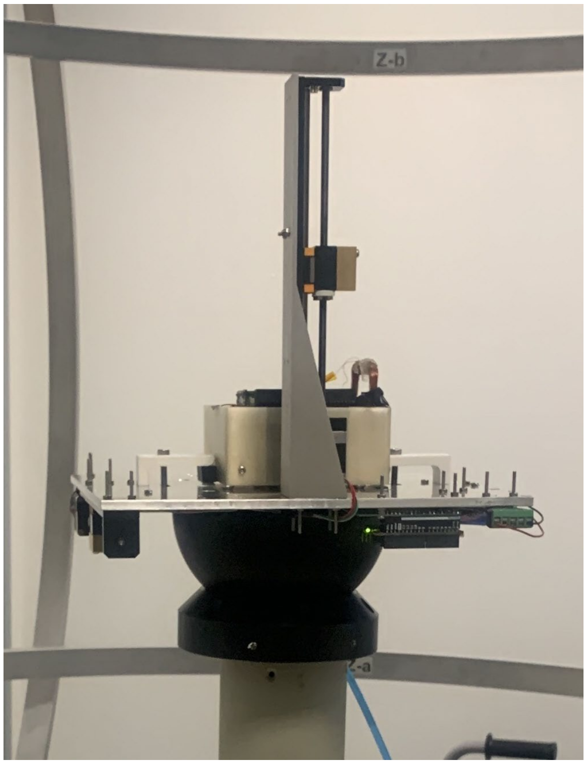

Figure 5: The air bearing table with the Polito mock-up mounted on it

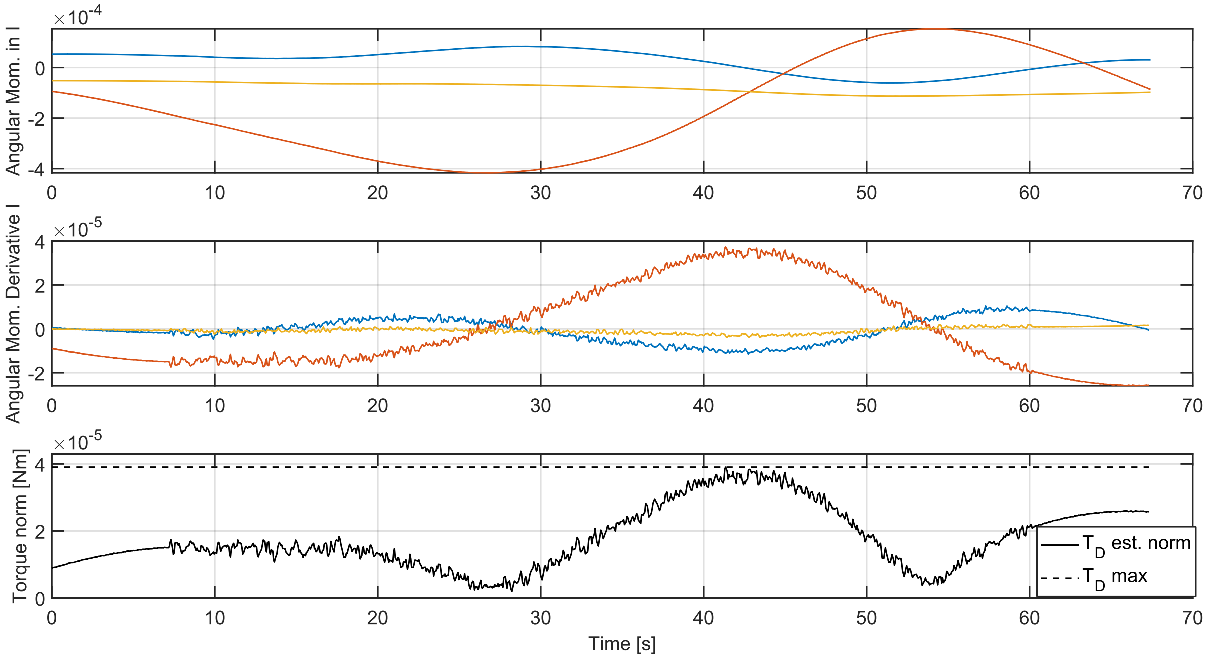

Figure 6: Result of the balancing process. From top to bottom: 1) angular momentum evaluation from filtered angular velocity data; 2) angular momentum derivative; 3) estimated residual torque

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