CubeSat Ground Test Facility as a Tool for Collaborative Hands-On Education: The Joint Experience of the u3s and STAR Laboratories

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CubeSat Ground Test Facility as a Tool for Collaborative Hands-On Education: The Joint Experience of the u3s and STAR Laboratories.

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Abstract: This manuscript reports on the educational outcomes of a joint initiative from the u3S Laboratory at the University of Bologna and the STAR Laboratory at Politecnico di Torino for a distributed, CubeSat-class attitude determination and control systems testing environment. The u3S laboratory is in charge of the dynamic testbed that hosts the nanosatellites mock-ups developed at the STAR laboratory. The verification campaigns are planned remotely between the students' teams of the two laboratories and culminate with the test execution at the u3S lab premises. Such a collaborative approach is intended to provide the next generation of aerospace engineers with a valuable hands-on training experience in spacecraft attitude control.

Keywords: CubeSats, satellite testing, hands-on education, laboratory equipment

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1. INTRODUCTION

With the rapid increase in the number of nanosatellites in orbit, there is a significant focus on improving the reliability of these small platforms. The CubeSat standard, in particular, has gained increased popularity, being widely adopted for educational (Cappelletti C., Hussain T., Johnson K., 2020) (Stesina, Corpino, 2020), (Barschke, 2020), (Rose et alii, 2023) scientific (Liddle, J.D., Holt, A.P., Jason, S.J. et al., 2020), (De, Abegaonkar, Basu, 2022), and commercial (Tsitas SR, Kingston J. 2012), in orbit demonstration and servicing (Corpino et alii, 2022) and interplanetary space missions. However, some of those missions experience failures (Gao, 2018) or require extended commissioning periods to address issues arising from on board systems (Stesina, Corpino, 2020), such as the Attitude Determination and Control Systems (ADCS) while in orbit.

A potential mitigation to such ADCS-related issues is through extensive ground verification (Stesina F. Corpino S., Feruglio L. 2017). On the other hand, to enable on-ground verification of spacecraft attitude control hardware and software, the biggest challenge to overcome is that of providing an orbit-representative testing environment.

Towards this end, the u3S - Microsatellites and Space Microsystems Laboratory at the University of Bologna and the Systems and Technology for Advanced Research (STAR) Laboratory (Stesina F. & Corpino S., 2021) at the Politecnico di Torino started a collaboration aimed at developing a distributed lab for manufacturing and testing nanosatellites' Attitude Determination and Control Systems. This initiative allows both research groups to collaborate on joint educational and research activities. The project involved the development of dedicated mechanical interfaces at the University of Bologna's lab, the creation of a custom ADCS mock-up compatible with the 1U form factor at the Polytechnic University of Turin's lab, and a collaborative hardware integration and testing campaign. A preliminary integration campaign was conducted in spring 2023 at the University of Bologna premises using some provisional hardware and interfaces (Curatolo et al., 2023). The results and lesson learnt served as a baseline for the new integration and test campaign conducted in spring 2024 and hereafter described.

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2. THE CubeDynA FACILITY AT THE u3S LAB

CubeDynA (CubeSat Dynamic Attitude simulator testbed) is a dynamic testbed for CubseSat-class attitude determination and control systems verification in a representative environment. It embeds various subsystems to simulate the attitude dynamics environment encountered by a S/C in Low Earth Orbit (LEO), including:

- an Air Bearing Table (ABT) equipped with an Automatic Balancing System (ABS) that provide three-degree-of-freedom rotational motion with low disturbance;
- a triaxial Helmholtz cage to simulate the Earth's magnetic field;
- a Sun simulator;
- a metrology system for generating ground-truth attitude data.

The facility is comprehensively described in (Modenini, D. et alii 2020), with key features summarized here. The ABT and ABS allow to replicate the attitude dynamics of a satellite in space, where external torques on a nanosatellite in LEO can be as low as 10^{-6} Nm (R. Sutherland, I. Kolmanovsky and A. R. Girard, 2019). For ABT based rotational motion simulators, the primary disturbance torque is the gravity torque resulting from misalignment between the Centre of Mass (CM) and Centre of Rotation (CR), which must be minimized. This is achieved by adjusting the relative position of the CR and CM through a balancing process. Coarse balancing is accomplished by evenly distributing the mass of platform components and by manual placement of counterweights on the rotating platform. Fine balancing is instead achieved using a set of three mutually orthogonal sliding masses moved by stepper motors thanks to a two-steps procedure. First, the in-plane masses positions are adjusted through a PID feedback control; afterwards, the out-of-plane mass displacement is computed through a system identification algorithm by sampling the ABT free oscillations, as detailed in (Bahu, A., Modenini, D., 2020).

The Helmholtz cage simulates the magnetic field in LEO, enabling the use of magnetic field sensors and magnetic actuation on satellites. A magnetorquer and closed-loop control system ensure precise tracking of the magnetic variation encountered in orbit. The Sun simulator uses a LED lamp to mimic the visible spectrum of the Sun's emission.

The metrology system includes a COTS, calibrated, marker-based stereo-motion capture system. Two ABTs have been developed capable of hosting payloads of different mass ranges up to 4 kg.

A second-generation of the facility is currently under development at the lab under ESA’s contract, and will be installed at ESTEC premises. The newly designed facility will offer several improvements over its predecessor, including:

- the support for a wider range of CubeSats, from 1U to 12U, allowing them to be placed on the rotating platform in any orientation;
- a newly designed, larger Sun simulator using a metal-halide source and equipped with an adjustable Sun-lamp beam orientation which can be changed from an overhead to a horizontal position;
- an additional lamp to simulate the effect of Earth Albedo.

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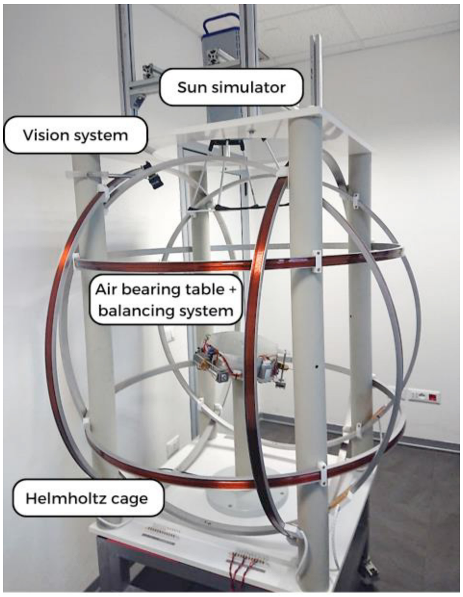

Figure 1. ADCS Facility at u3S Lab

3. STAR LAB CUBESAT ADCS MOCK-UP

Since 2008, many avionics systems were developed at STAR Lab of Politecnico di Torino, especially for small space platforms both for on-ground services (Stesina, 2019) and for space missions (Busso e alii, 2016). Among others, major efforts have been dedicated to Attitude Determination and Control Systems for small satellites. Innovative algorithmic solutions (Pecorilla M., Stesina F., 2024) and combined hardware and software in System on Module (SOM) up to testing tools and facilities have been designed, tested and validated through data from the orbit. The most recent work is presented in this paper, i,e, the new ADCS system for the future 3U Cubesat developed by the Cubesat Team of Politecnico di Torino.

The ADCS is constituted by a microcontroller that manages the communication with the functional board, acquires measurements from all sensors, runs ADC algorithms, commands the actuators via a PWM logic drivers. The sensors are an inertial measurement unit, with a tri-axial magnetometer, three accelerometers and three gyroscopes, and sun sensors developed in house (not mounted in the first version). The actuators are three magnetic torquers and reactions wheels (these latter not integrated in the tested mock-up) controlled setting the current through an H-bridge. The ADCS determines and controls attitude and angular velocity platform. It takes operative commands by the user and passes telemetry to *the functional board* (via UART). Simple control laws are implemented for detumbling mode and one-axis pointing. There are two main Operative Modes (OpModes).

The first version of the ADCS is the test object for the test campaign at the u3S laboratory.

The ADCS system has been integrated on a Cubesat Test Platform (CTP). Beyond the ADCS, the platform has a *functional board* has been designed and manufactured with the following tasks: to provide regulated voltages from a battery pack installed on base of the structure, to allow the battery recharge without removing the pack from the platform, to manage the onboard command and data handling and synchronization of the communications between the ground system and beyond the ADCS. The data interfaces with the ground are guaranteed (every 5 seconds) through the WiFi module (to avoid any wired line that would jeopardize the torque balancing of the entire system) of the Raspberry Pi Zero, that is the microcontroller, while the communications with the ADCS occur via RS232 line every second. The core software of the On-Board Computer (OBC) automatically starts after every boot and consists of a python program subdivided into four threads:

- Command and Data Handling (CDH) thread: this is the “main” thread, whose purpose is, as the name suggests, getting commands from the user and handle data from ADCS, implementing the communication logic with the latter.
- Client thread: this thread is responsible of communication with the user, which is performed through another program (Client) which uses an Unix socket as channel, similarly to how the Telegraf software does.
- Log thread: is the one responsible of logging data, both to Telegraf and optionally to a local log file.
- ADC thread: manages and samples the OBC’s ADC.

The ADCS and OBC boards exchange data through the UART protocol, in particular :

- The OBC sends to the ADCS board OpMode packets and Target (desired angular velocity) packets, together with information about internal power state (coming from its ADC)
- The ADCS board sends to the OBC packets containing the Inertial Measurement Unit (IMU), temperature sensors and actuators currents readings.

The structure is made with additive manufacturing techniques in PLA, a material that provides sufficient structural strength with low density, resulting in the minimum structural mass. The total mass of the system is 430 g.

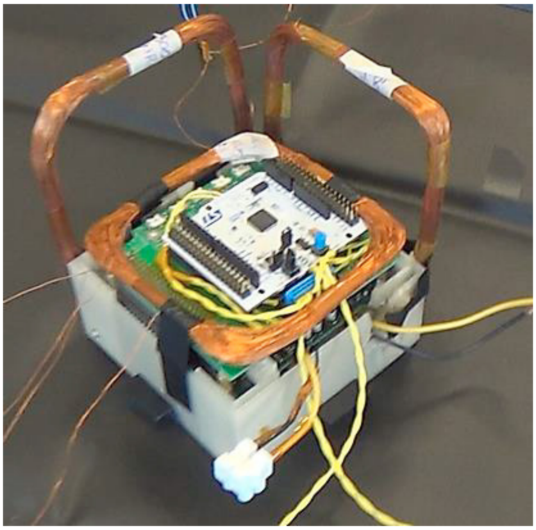

Figure 2: the Cubesat Test Platform.

4. PLATFORM INTEGRATION AND SYSTEM BALANCING

The CubeDynA platform allows hosting satellites of the CubeSat form factor with mechanical contact only with the Cubesat’s rails. In the case of the CuebeSat Test Platform, the mechanical interface happens with lower part of the platform, while the top part is left open for an easy access to the electronic board. Coarse balancing is needed to compensate for the macroscopic offset between the CM and the CR of the platform. In this particular case, coarse balancing required distributing 0.8 kg of counterweights on the platform. Overall, the total weight of the platform results to be equal to 7.404 kg. The CTP and the counterweights on the ABT are shown in Figure 3.

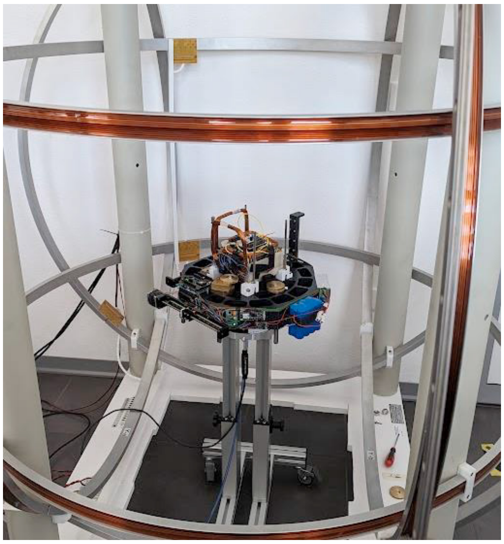

Figure 3: the Cubesat Test Platform on the CubeDynA ABT inside the Helmholtz cage.

Fine balancing consists of two steps: in-plane balancing where the horizontal component of the CM to CR offset is compensated and the vertical offset estimation and compensation. The two steps are iterated until the offset estimated value does not decrease further. Figure 4 shows the normalized horizontal components of the gravitational acceleration, horizontal components of angular velocity and stepper motors' carrier position during the in-plane balancing process. The in-plane balancing process is considered completed when the horizontal components of the gravitational converge to zero. Figure 5 shows the residual torque estimation and the CM to CR offset estimation. The residual torque RMS results to be equal to $6 \times 10^{-5} Nm$ and the peak value $1.5 \times 10^{-4} Nm$.

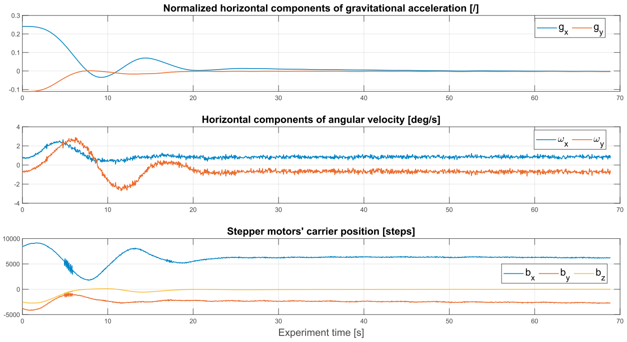

Figure 4: normalized horizontal components of the gravitational acceleration, horizontal components of angular velocity and stepper motors' carrier position during the in-plane balancing process.

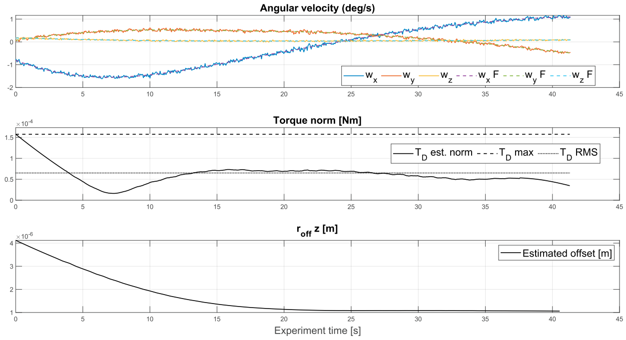

Figure 5: angular velocity, residual torque estimation and offset estimation

5. TEST CAMPAIGN

The first experimental session of the CubeSat Test Platform within the CubeDynA facility was aimed at: 1) validating the measurements gathered by the IMU and 2) verifying the correct polarization of the magnetic torquers.

5.1 IMU characterisation

The CubeSat's IMU measurements have been compared to the angular speed velocities recorded by the ground-truth instrumentation of CubeDynA, which was already calibrated.
The execution of the test consisted of moving the CTP starting from a random initial attitude to an attitude for which one axis of the CTP is aligned with the direction of the magnetic field generated by the Helmholtz cage.

Due to the different sampling rate, a mask with values collected at the same time tag was matched. The difference (Δω) between the reference values and the IMU measurement are shown in Figure 6. Red, blue, and green bars report the difference of measurements of angular velocities along x, y and z respectively. The mean error was [-0.00273, -0.0021, 0.00466] rad/s, with standard deviation of [0.0155, 0.0412, 0.0231] rad/s and a distribution resembling a Gaussian one, so we can consider the selected IMU accurate enough for the future application.

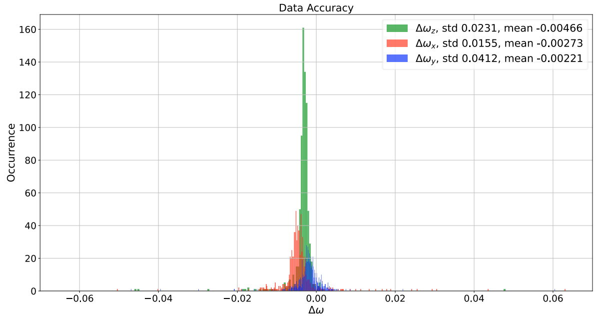

Figure 6: mean and standard deviation of the error on the angular rate measurements.

5.2 Polarity test

A polarity test of the magnetorquers dipoles has been conducted. The test consisted in checking that the dipole commanded to the magnetorquers is actuated in the correct direction. Using the Helmholtz cage, a magnetic field in a direction perpendicular to the local vertical is created. If the magnetic dipole is actuated in the correct direction, it is expected that the CubeSat aligns the positive dipole direction to the magnetic field lines.

This test foresaw that the currents flowed in the actuators first in clockwise and then in anticlockwise directions. CTP started to rotate from a random attitude and a duty cycle of 90% is applied via PWM driver and circuits up to the alignment with the Magnetic Field direction. Then, a duty cycle of –90% is applied and CTP started rotating in the opposite direction.

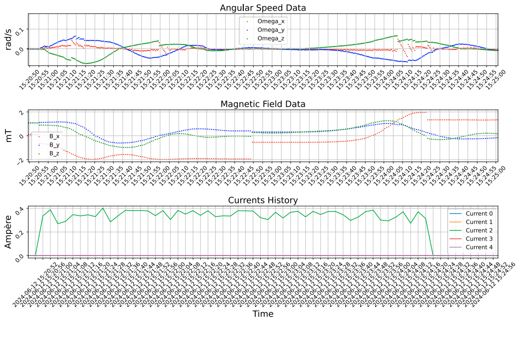

Figure 7: trends of angular velocity (top panel), measured magnetic field (central panel) and current consumption (bottom panel)

Figure 7 shows the results of actuation of the magnetic torquer mounted on the +X face of the CTP. The top panel depicts the evolution of the angular velocity. It is possible to see that there is an increment of the velocity then a slowing down (with an overshoot) followed by a stable attitude condition (no rotation). Then, the inversion of polarisation is applied, and a similar trend, but with opposite sign, is observed with a lower overshoot up to reach the stable attitude. The bottom panel shows the current flowing inside the magnetic torquers, which exhibits a variation of 50 mA of amplitude. This variation is not negligible: we confirm that the current that flows inside the magnetic-torquers is constant and the significant variation of the measurements is due to the acquisition circuit, requiring an improvement of this latter. On the contrary, no ripple on the measured values is observed, confirming that the filtering stage works properly. These results suggest that the magnetic actuators embedded in the CTP mock-up can indeed be exploited for attitude and angular velocity control.

6. CONCLUSIONS

Three main types of conclusions can be drawn from the activity reported in this manuscript, namely: 1) technical, 2) programmatic, 3) educational. For the technical standpoint, the results obtained during the first test campaign are promising, considering that the CTP, completely developed by students at Politecnico di Torino, is a brand new development and faced for the first time a functional test session in a relevant environment. While its actual attitude control capabilities need to be further investigated, the expected functions and operations of the overall CTP were demonstrated. Moreover, the integration of CTP in the CubeDynA facility at the Forlì Campus of University of Bologna was successfully completed, paving the way for future sessions. This integration includes also the validation of data, electrical, and mechanical interfaces, demonstrating that remote cooperation between the two students teams was effective. The educational return was great in this sense because the exchange of information is never trivial, as it is often experienced also by professionals involved in larger projects. Clearly, mistakes and drawbacks appeared during the integration, but this is part of the learning experience. However, thanks to the constant interactions the student teams were able to find quick answers and corrective actions to solve misbehaviors.

Moreover, such a project requires cross-skill and multidisciplinary knowledge. Hardware and software are prevalent and students with skills in electronic, telecommunication and computer science engineering cover a relevant role. The contribution of students with background in aerospace engineering and system engineering is also fundamental: the former add specific know-how on avionics aspects and the latter give a relevant contribution on the requirements definition, AIV planning and execution and interface with all parts of the system.

Eventually, students skills, attitude and motivation need to converge to create a team, not a group. Team means defining roles and responsibilities: everyone can contribute but each task has a responsible in charge that takes care of the correct and timely execution and reports the status of the activities to the management.

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