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Nanosatellite-class dynamic attitude simulator for hands-on aerospace control education

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Abstract: Due to their low size, mass, development cost and time, nanosatellites have become an increasingly popular tool at universities for providing students with hands-on experience in aerospace education. Among spacecraft subsystems, the attitude determination and control one surely represents a fruitful resource for practicing aerospace control applications. To enable on-ground verification of spacecraft attitude control hardware and software, however, the biggest challenge to overcome is that of providing a representative testing environment. Towards this end, at the μ3S laboratory at the University of Bologna a dynamic hardware in the loop facility has been developed, which allows for testing attitude control subsystems of nanosatellites in the range of 1U to 3U, according to the CubeSat form factor. This paper describes the educational impact that the facility has been having, during both its development and commissioning phases, as well as its early use as a testbed for CubeSats attitude control, which is currently focused on magnetic-based actuation.

Keywords: Laboratory equipment; HIL/SIL; Aerospace control systems technology; CubeSats.

1. INTRODUCTION

In the past few decades, the reduction in size of spacecraft equipment, such as sensors, actuators, batteries and payloads, paved the way to the so called small-satellites era. With size and weight being only a fraction of conventional satellites, and following the components standardization enabled by the well-established CubeSat form factor, nanosatellites have become very popular in the academia, where budget constraints are often the main design driver.

As a result, the educational impact of nanosatellites in general, and CubeSats in particular, on aerospace engineering university programs is well recognized since a decade at least, see *e.g.* Larsen and Nielsen (2011). As far as the automatic control aspects are concerned, the Attitude Determination and Control Subsystem (ADCS) of a spacecraft offers a plethora of potential applications, but also great challenges. Not only is one of the most complex and mission-critical subsystems, but its end-to-end verification and testing is hard to be achieved on ground.

In this paper, the experience gathered at the Microsatellites and Space Microsystems (μ3S) laboratory while developing and operating a facility for the dynamic, hardware-in-the-loop testing of nanosatellites' ADCS is presented, focusing on the educational outreach.

The rest of the manuscript is organized as follows. First, an overview of the facility is given, presenting the main subsystems and its key features (Section 2). Then, Section 3 presents a selection of three control oriented tasks, successfully tackled by students as part of their internship or final project. Finally, Section 4 summarizes the main outcome and expected near future developments.

2. NANODYNA FACILITY AT μ3S LABORATORY

During the past four years, a three-degrees of freedom Nanosatellite-class Dynamic Attitude testbed (NanoDynA) has been developed at the μ3S laboratory of the Department of Industrial Engineering at University of Bologna. The laboratory started its activities in 2003 with the ALMASat-1 project, a microsatellite launched in February 2012 on board the VEGA maiden flight.

In this section, we will briefly review the architecture and main characteristics of the NanoDynA facility, while the details of the development and commissioning of all its equipment can be found elsewhere, see Modenini et al. (2020).

The testbed has been designed for serving both educational and research purposes, targeting nanosatellite-class ADCS applications. Due to the large variety of deployed nanosatellite missions, whether on or beyond Earth orbit, a single facility could hardly fit the needs of the entire range of ADCS hardware combinations testing. Throughout the development, we considered as the target application scenario the one of nanosatellite missions in Low Earth Orbit (LEO) having medium pointing accuracy requirements, i.e. in the order of 1 degree. A size range of 1U to 3U was taken as a reference (a 1U CubeSat standard corresponds to a cubic volume of $10\times10\times10$ cm^3), being the most commonly employed in academia, Kulu (2021).

The core of the testbed is an articulated stand featuring a table-top spherical air bearing platform, which is a widespread

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configuration, see e.g. Kim et al. (2001), whose function is to hold the nanosatellite mock-up under test (MUT) and allow for an almost frictionless rotational motion. It includes an automatic balancing system with shifting masses actuated by linear motors. Two versions of the rotating platform have been developed: a first, larger one, conceived for MUT having size ≥ 3U, and a second one for MUT having size in the order of 1U. A programmable CubeSat mockup is available for simulations and control laws testing. Other subsystems are:

- a Helmholtz cage for geomagnetic field simulation. The rationale for that is that most Low Earth Orbit satellites relies on the geomagnetic field both for attitude determination and control.
- A Sun simulator for testing of sun sensors, based on a LED studio light equipped with a custom collimated lens.
- A metrology system for ground-truth attitude measurement, which is based on a calibrated monocular vision system, entirely developed in house.

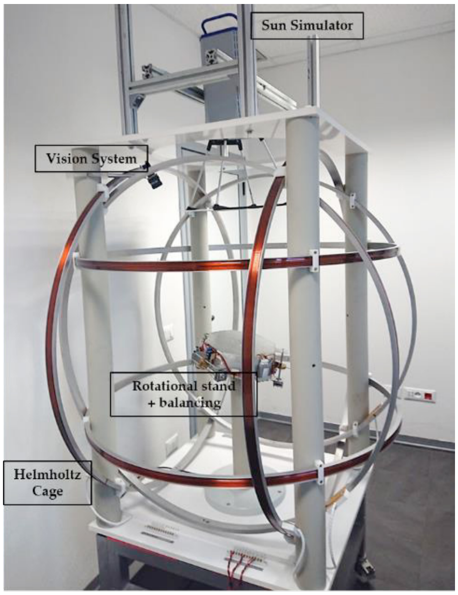

Fig. 1 The dynamic testbed equipped with the 3U rotating platform, from Modenini et al. (2020).

Its key features are (Bahu (2020)):

- Designed for students by students. The facility is intended to grow in the near future, by implementing new environmental simulation capabilities, such as a starry sky simulator for star sensing. Newly added capabilities will enable testing of different ADCS mock-up, thus enabling new hands-on projects.
- Functional testing capabilities. An almost disturbance-free microgravity environment is provided for dynamical simulations. The main design goal was to reduce the residual disturbances magnitude down to a value comparable to that acting on nanosatellites in Earth orbit, thereby enabling verification in representative conditions.
- ADCS HIL simulations. The facility features on-orbit environmental simulation capabilities (such as sunlight, magnetic field, etc.) for comprehensive hardware testing.
- Control laws testing: the facility integrates programmable hardware which can simulate ADCS functionality and allows comparing different attitude control laws.

Despite a few facilities with these characteristics already exist for purchasing as turn-key solutions, an in-house development was preferred in our laboratory for two reasons, namely i) budget constraints and ii) the educational potential intrinsic in self-development. On the other hand, a major drawback of such approach is that guaranteed performance levels are hard to be achieved and extensive characterization campaigns are required to properly assess them. As a result, development time may grow significantly before adequate performance can be obtained.

Since the beginning of its development, the testbed was made available to the students of the Master of Science in Aerospace Engineering of the Alma Mater Studiorum Università di Bologna, at Forlì Campus, representing a source of internships and final projects especially for those students enrolled to the course in Spacecraft Attitude Dynamics and Control.

3. CONTROL APPLICATIONS USING A DYNAMIC ATTITUDE SIMULATOR

During the past four years, NanoDynA testbed offered several opportunities of hands-on control theory applications.

A remarkable feature of employing a self-developed dynamic attitude testbed is that a number of automatic control problems arise as part of the facility development itself, i.e. without having an actual MUT equipped with sensors/actuators. Examples include the closed loop control of the magnetic field generated by the Helmholtz cage, or the automatic balancing system for reducing the gravity torque acting on the rotating platform.

In the remainder of this section, we will focus on three control projects related to the facility development, assigned during the past Academic Years, namely:

- AY 2016-17: Closed loop control of the generated magnetic field from a Helmholtz cage.
- AY 2109-20: Automatic balancing system for a 3U rotating platform.
- AY 2020-21: Magnetic detumbling for a 1U CubeSat mock-up.

3.1 Closed loop control of the Helmholtz cage

As part of a Master of Science final project, a closed loop control of the Helmholtz cage generated magnetic field was implemented and tested. The main goal of the project was to enable the accurate tracking of a time-varying reference signal like the one expected in LEO. To this end, a flux-gate magnetometer (model AP539 from Applied Physics) was placed inside the pedestal support of the articulated stand, and a calibration procedure was implemented to compute magnetometer's scale-factors and biases, as well as the misalignment matrix between the cage and the magnetometer itself. The set-up was then completed by a programmable power supply and a switch for bipolar current control. The implemented feedback control allowed to maintain the error between the measured and commanded magnetic field below 0.2% (≈ 0.5 mGauss), see Fig. 3. Care has also been taken towards making the system usable for future students, by providing an intuitive graphical interface make the sensor calibration and magnetic field generation processes highly automated.

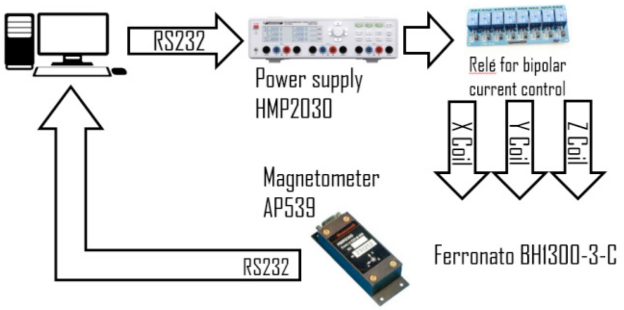

Fig. 2. Schematic representation of the control closed loop control for the Helmholtz cage, adapted from Modenini et al. (2020).

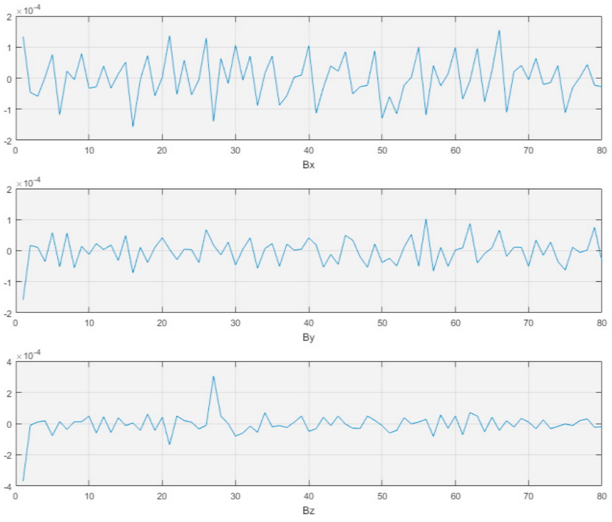

Fig. 3. Percentage error between commanded and measured magnetic field within the Helmholtz cage.

3.2 *Automatic Balancing System*

Ideally, a facility for dynamic testing of spacecraft ADCS shall ensure an almost disturbance free rotational dynamics. For the targeted nanosatellite missions in LEO orbit, typically the overall disturbance torque magnitude lies in the order of 10^{-6} Nm, which is an extremely low value to achieve on ground. For a spherical air bearing, the largest disturbance torque is the one due to unbalance, i.e. the torque arising from the offset between the center of rotation (CoR) and the center of mass (CoM) of the rotating equipment, an offset which must be ideally cancelled. Even though, in principle, balancing can be performed manually by an operator, an automated procedure is to be preferred as it may guarantee higher performance (Chesi et al. (2014)).

For our facility, we developed an automatic balancing system (ABS) consisting of a set of three mutually orthogonal shifting masses, whose position is adjusted to bring the CoM onto the CoR. The project involved a Master student, which took care of the mechanical design, structural analysis, and assembly of the rotating platform equipped with the ABS hardware (see Fig. 4), plus a PhD candidate which oversaw the electronics programming and control law design and verification.

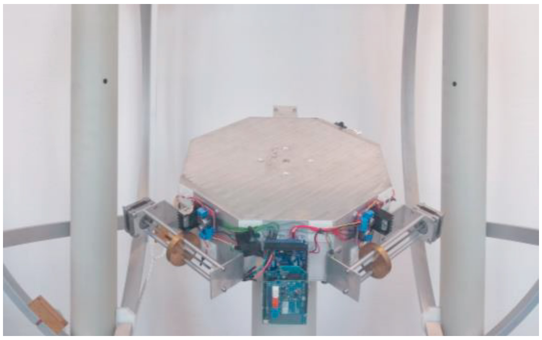

Fig. 4. The articulated stand equipped with rotating platform for 3U sized mock-up, featuring the automatic balancing system.

From a control standpoint, the task can be tackled whether as a system identification or as a feedback control problem. In the former case, the CoR-to-CoM offset is estimated, possibly jointly with the inertia matrix, after sampling of the free platform oscillations. In the latter, the control action (mass displacement) is adjusted in real-time to balance the platform in the horizontal plane by aligning the symmetry z-axis to the local gravity direction, as in Fig. 5. This is the approach followed for our ABS: full implementation details can be found in Bahu and Modenini (2020).

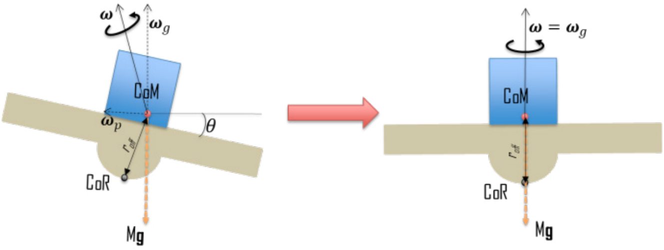

Fig. 5. Conceptual sketch of the plane balancing problem for a rotating platform.

Note that, by adjusting the shifting masses locations, the resulting torque is always constrained to lie in the local horizontal plane, thereby preventing any control action about the local vertical. The practical impact is that the balancing can effectively cancel out the CoR-to-CoM offset only limited to the x-y components. The residual z-offset shall instead be identified and compensated in a subsequent step.

The study of the plane balancing problem was used to highlight performance differences between SISO linear control synthesis and nonlinear feedback based on Lyapunov method. In the former case, the feedback laws about x-y body axes were designed as decoupled PID channels, while in the latter full coupling between axes could be accounted for according to the rigid-body dynamics (Bahu and Modenini (2020)).

Different response of the system orientation in terms of pitch and roll angles were obtained when performing in plane balancing, with the nonlinear controller guaranteeing faster convergence then the PID one. Trying to reduce the convergence time of the linear controller by increasing the gains magnitude, eventually drives the closed loop system to instability.

3.3 Magnetic detumbling

During the past months, the first control application was successfully tested on NanoDynA, thanks to the small table-top rotating platform hosting a 1U CubeSat mock-up, see Fig. 6.

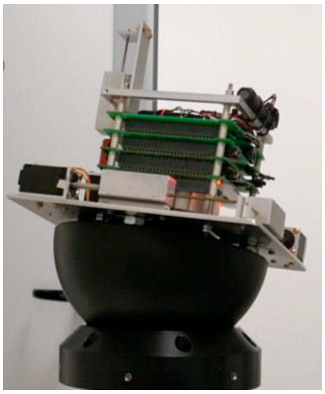

Fig. 6. 1U CubeSat mock-up equipped with ABS on top of the spherical air bearing.

It consisted of a COTS mock-up (ESAT, from Theia Space) equipped with a set of three mutually orthogonal magnetorquers capable to generate 0.8 Am^2 of magnetic dipole each. The MUT was mounted on a table-top platform, made of amagnetic aluminium, which accommodates an appropriately sized ABS, conceived as a reduced-scale version of that described in the previous paragraph.

The control scenario is that of a detumbling maneuver, which is the operation, usually performed by a spacecraft soon after separation from the launching vehicle, to damp the unwanted rotational kinetic energy imparted by the separation system. This operation can be done by magnetic actuation alone through the well-known B-dot control law, Avanzini and Giulietti (2012):

$$\boldsymbol{m} = -k\, d\boldsymbol{b}/dt \tag{1}$$

where $\boldsymbol{m}$ is the control dipole and $\boldsymbol{b}$ is the magnetic field vector measurement. This control law is very simple, as it needs only magnetic field measures and is robust to measurements biases. The onboard dipole interacts with the environmental magnetic field generating a control torque equal to $\boldsymbol{\tau} = \boldsymbol{b} \times \boldsymbol{m}$.

A spacecraft under magnetic actuation only is instantaneously underactuated, since no torque can be exerted parallel to the magnetic field direction. Therefore, for being able to effectively dissipate the spacecraft angular kinetic energy, a time varying magnetic field is required (which is why a magnetic detumbling maneuver is more effective on orbital planes highly inclined with respect to the geomagnetic equator).

The control system for the Helmholtz cage was then used to generate a magnetic field variation similar to that encountered in a polar orbit, as predicted by the IGRF model, but with artificially increased magnitude and frequency. The former is needed to achieve sufficient control authority against the residual disturbance torque acting on the platform, whose magnitude has been estimated to be up to $5 \cdot 10^{-5}$ Nm. Note that this value is more than an order of magnitude greater than the one expected in orbit for a 1U CubeSat. The increase in the magnetic frequency, instead, is required to limit the duration of the experiments to an extent where the dissipative effects introduced by the air bearing friction are significantly lower than the ones of the control action. A sample outcome of a detumbling is depicted in Fig. 7, where the decay of the angular rate magnitude with free oscillations (no actuation) is compared to that induced by magnetorquers commanded according to Eq. (1).

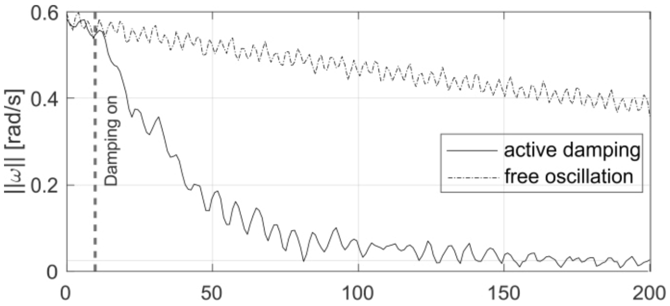

Fig. 7. Experimental magnetic detumbling: comparison between free oscillations and damping using magnetorquers, adapted from Bahu (2021).

Thanks to the full control of the magnetic field generation inside the facility, some interesting characteristics of underactuated control can be captured through the experiments. For example, it is possible to observe how the time required to complete a detumbling is directly linked to the period of the magnetic field variation: the shorter this latter, the faster the detumbling manoeuvre can be.

4. CONCLUSIONS

Facilities for dynamic attitude determination and control testing are showing a great potential in Aerospace engineering education, which is testified by the many examples being built by academic and research institutions worldwide. As far as our experience is concerned, the dynamic attitude control testbed at the u3S laboratory proved a useful source of hands-on projects for some ten undergraduate and graduate students, plus a PhD candidate. Up to now, most of the applications were focused on the facility development and commissioning, and only recently the first successful testing of attitude control laws for a 1U CubeSat mock-up was achieved, using magnetic actuators. Apart from the example of magnetic detumbling reported herein, single-axis, de Ruiter (2011), and triaxial magnetic attitude control laws are being tested, Lovera and Astolfi (2004), Psiaki (2000).

For the next future, we aim at increasing the set of actuators available for experimental attitude control applications: a graduate project which is ongoing at the moment of writing is dedicated to the design of a cluster of three reaction wheels.

Another step forward would be implementing some degree of facility standardization, to enable sharing of hardware and software between different universities. Although a complete standardization might be hardly achievable, and perhaps not even desirable, some of the key design elements could indeed be made repeatable, for example:

- Spherical air bearing design, exploiting e.g. 3D printed solutions.
- Automatic mass balancing system.
- Programmable processing units, switching from the proprietary ESAT system to a more widespread solution such as the Raspberry PI or Arduino.

While implementing this way-forward, we trust that NanoDynA facility will keep serving as a useful hands-on educational tool for many aerospace engineering students.

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