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High-Level Strategies for the Rapid Development of an AOCS Simulator for a Student-Designed CubeSat Mission / Niero, Luca; Rotti, Valentina; Scotti, Leonardo; De Nichilo, Gaetano; Canzoneri, Raffaele; Campioli, Serena; Stesina, Fabrizio; Corpino, Sabrina. - ELETTRONICO. - (In corso di stampa). (5th Symposium on Space Educational Activities Munich (GER) 8-11 April 2026).

Publisher:
Technical University of Munich

Published
DOI:

High-Level Strategies for the Rapid Development of an AOCS Simulator for a Student-Designed CubeSat Mission

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Abstract

This work presents the strategies adopted and lessons learned during the development of an Attitude and Orbit Control System (AOCS) simulator for a CubeSat mission designed by students. The case study focuses on the ELECTRA mission, developed by the CubeSat Team PoliTo, and selected for the “ESA Fly Your Satellite! Design Booster 2” programme. The AOCS development, specifically, brought together a sub-team of students with heterogeneous academic backgrounds and different levels of education. Working collaboratively, the team designed and implemented an AOCS simulation tool with a hierarchical architecture to support system design and validation.

The simulator was implemented leveraging Simulink’s integration capabilities alongside Matlab functions and toolboxes, with support for code generation aimed at onboard rapid prototyping. A top-down design approach was adopted to decompose the system into its main components, with algorithms, sensors, actuators, and plant blocks at the higher level. This resulted in a multi-layered simulation architecture, where upper layers manage mission-level inputs and outputs, while lower layers manage navigation and control algorithms, system and hardware characteristics, and attitude and orbital dynamics. This modular structure enhances scalability, facilitates debugging, and improves system awareness, while also enabling efficient task allocation according to the students’ expertise. To accelerate development in a student-driven environment, several simplifications were introduced, such as the use of pre-built functions and simplified models. The high-level input-output structure allows for rapid performance benchmarking against validated external tools, notably System Tool Kit, supporting verification and validation process.

The initial version of the simulator was completed within approximately six months in a volunteer-based student environment. Extensive algorithm testing has been conducted, integrating all blocks and verifying compliance with mission objectives and requirements. Future developments will focus on extending the simulator toward hardware-in-the-loop testing and onboard software integration, thereby establishing a reusable framework for educational and research applications in small satellite design.

Keywords: CubeSat, AOCS, Digital Twin, GNC, Education

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Nomenclature

Bold is used for vectors and matrices, normal for scalars.

a	*Acceleration*
B	*Magnetic field*
C_D	*Drag coefficient*
h	*Angular Momentum*
I	*Inertia*
J_2	*First zonal harmonic*
m	*Mass*
m_{mag}	*Magnetic dipole*
μ	*Gravitational parameter*
N	*Coil windings*
ω	*Angular velocity*
q	*Quaternion*
ρ	*Atmospheric density*
r	*Position*
S	*Surface*
T	*Torque*
v	*Velocity*

Acronyms/Abbreviations

AIL	*Algorithm-In-the-Loop*
AOCS	*Attitude and Orbit Control System*
APF	*Artificial Potential Field*
EGM2008	*Earth Gravitational Model 2008*
GNC	*Guidance, Navigation and Control*
GVE	*Gauss' Variational Equations*
HIL	*Hardware-In-the-Loop*
HPOP	*High Precision Orbit Propagator*
PWM	*Pulse-Width Modulation*
RW	*Reaction Wheel*
SMC	*Sliding Mode Control*
STK	*System Tool Kit*
TEC	*Total Electron Content*

1. Introduction

ELECTRA is the main mission developed by the CubeSat PoliTo Team, a student group from the Politecnico di Torino with a twenty-year tradition of research, development and launch of small satellites [1]. Leveraging a 3U CubeSat platform, the mission's scientific objective is to study the ionospheric Total Electron Content (TEC) [2] while the technological objective is to demonstrate an innovative electric propulsion system for orbit raising. Both objectives require an Attitude and Orbit Control System (AOCS) that is reliable, available and has a low impact on the project in terms of size, cost and computational effort. A preliminary system iteration led to the definition of three magnetorquers as attitude actuators, while magnetometers, an inertial measurement unit and Sun sensors are employed for attitude determination.

A modular Matlab/Simulink framework was developed and tested [3] following the work of [4] to support the design of the system, and to verify the performances of various guidance and attitude control algorithms through Algorithm-In-the-Loop (AIL) [5]. The tool has therefore been developed with an emphasis on high-fidelity modelling of the dynamic and kinematic behaviour, while adopting a simplified representation of the hardware to evaluate system dynamics, test robustness and stability, and tune the controller gains. The natural evolution of the project then foresees a validation phase through Hardware-In-the-Loop (HIL) testing, in which the dynamic model is simplified but the actuators are real hardware.

2. Simulator Architecture

The development of this simulator required numerous choices in terms of modelling and assembly, which are reported below as "Lessons Learned" from the project. The tool is organised into various levels of implementation. At system level, it features a classical closed-loop control scheme (Figure 1).

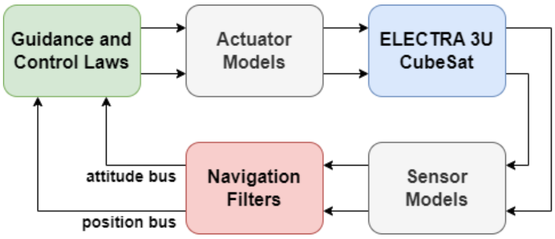

Figure 1: Closed-Loop System Architecture

Two virtual data buses respectively distribute position and attitude information: the plant reacts to control and disturbance actions, sensors measure the new state, navigation algorithms process measurements and predictions, guidance and control laws compute the correction, which is then translated into effects on the plant by the actuators. This subdivision comes from the need for simulating wrappers and parameters exchanges between satellite software and hardware, exploiting

Simulink capabilities to manage different frequencies and data packets, as well as having a structure ready for code generation and rapid prototyping.

2.1. *Plant Modeling*

In greater detail, each block features a specific internal structure, with the plant naturally divided into attitude and position dynamics (Figure 2). Several approaches were assessed for modelling the orbital motion, from the classical Keplerian two-body formulation to Gauss' Variational Equations (GVE), considering both osculating and mean elements. An incremental strategy was adopted: starting from the unperturbed dynamics, then adding the J_2 perturbation, and finally atmospheric drag.

In parallel, the high-fidelity propagator from Simulink’s Aerospace Blockset was validated against the High Precision Orbit Propagator (HPOP) in STK. The Simulink propagator proved accurate under specific conditions, particularly when using a fixed-step integrator and a 120 degrees Earth Gravitational Model (EGM2008) spherical, i.e. zonal, sectoral, and tesseral, harmonics model instead of the zonal-only J_2 analytical approximation. To ensure straightforward integration of the EGM2008 and future perturbations, a perturbed two-body formulation was therefore selected. Atmospheric density for drag modelling was computed using the NRLMSISE-00 model as validated using STK. Third-body perturbations (e.g., from the Moon or the Sun) have not yet been included, as the mission is confined to low Earth orbit. Nevertheless, the modular architecture of the model allows additional disturbance blocks to be incorporated in the near future with minimal effort. The position branch propagates the perturbed Keplerian equations [6].

Regarding the attitude block, the adopted approach relies on classical Eulerian rotational dynamics combined with a quaternion-based kinematic representation. After discarding Euler angles due to their well-known integration singularities, alternative parametrisations such as classical and modified Rodrigues parameters were evaluated. Nevertheless, quaternions were ultimately selected owing to their robustness and the extensive reference material available in the literature for Guidance, Navigation and Control (GNC) implementation. The attitude dynamics was pre-configured to include the angular momentum and control torques generated by reaction wheels (RWs), together with the main environmental disturbance torques. At the current stage, these include magnetic torque, gravity-gradient torque, and the effects induced by the J_2 harmonic. The Eulerian equations from [6] are used.

The attitude disturbance torques were modelled following established formulations available in the literature [7]. For the geomagnetic field representation, a tilted-dipole model was selected instead of the full International Geomagnetic Reference Field (IGRF) in order to reduce computational load. For a LEO orbit, a maximum relative error of approximately 20% was observed comparing the models.

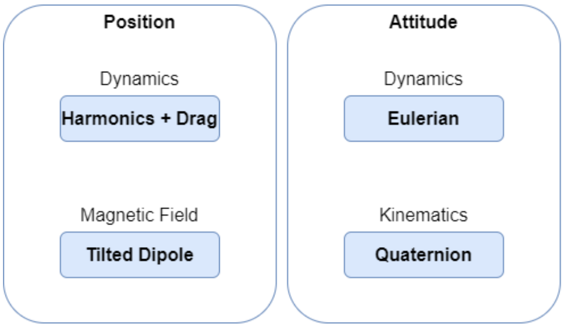

Figure 2: Plant Modeling

Finally, a solar propagator was included in the plant to enable the simulation of sun-pointing operations by computing the Sun vector at each time step. The Planetary Ephemeris block from Simulink’s Aerospace Blockset was used to ensure a rapid develoment of the tool.

2.2. *Guidance Modeling*

Regarding the selection of guidance algorithms, an initial survey of the state of the art led to the development of two main research directions (Figure 3). The first concerns static references, defined by constant quaternions and angular velocities. The second focuses instead on online algorithms, aimed at identifying guidance laws capable of generating position-dependent pointing slew manoeuvres.

Two cases of interest to be simulated were identified for static guidances: inertial stabilization and rate damping. Detumbling is the first guidance mode activated after the satellite is released from the launcher; this phase is essential to ensure that the angular velocity is reduced to near zero before initiating the commissioning of the payload and subsystems. At this stage, no specific reference quaternion is required, thus only angular velocity error are considered as control inputs. Inertial pointing is then considered as the first attitude maneuver check of the system correct functioning, enabling verification of the AOCS performance not only in terms of angular velocity regulation but also in terms of attitude pointing error. Through a series of switch-case routines, used to test the different algorithms according to the operational modes and mission phases, the two guidance laws are activated in separate simulation scenarios.

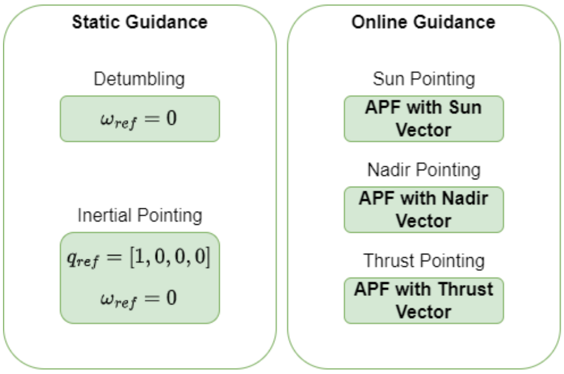

Figure 3: Implemented Guidance Laws

Moving toward the actual operational modes of the CubeSat, it is necessary to guarantee Nadir-pointing for scientific objectives, thrust-pointing for thruster demonstrations, and Sun-pointing to ensure power generation. To meet these requirements, an attractive Artificial Potential Field (APF) guidance law [8] was implemented by considering the relevant direction vectors. Based on the evolution of the desired quaternion, this algorithm provides the angular velocity required to follow the commanded attitude trajectory. The APF approach was selected for its quaternion-based formulation, and its inherent compatibility with the controllers described in the following sections.

Finally, the position-guidance modelling includes a dedicated logic for the activation and deactivation of the thruster, defined at system level in coordination with both the Mission Analysis team and the development of the power generation subsystem. In this first implementation, the manoeuvre was simulated assuming a scheduled shooting plan for the thruster ignition.

2.3. Control Modeling

The control subsystem, given the system architecture composed of three magnetorquers and three magnetometers, was developed around two main control laws (Figure 4). Input to these laws are the magnetic field measure, the quaternion error, and the angular velocity difference with respect to the guidance reference.

For the satellite rate damping, a B-dot controller was employed, as it is well known for its effectiveness in this specific function. The development of the attitude control, however, was considerably more challenging due to the actual limitations of the actuators. Indeed, simple controllers such as PID laws lack robustness on disturbances and suffer from under-actuation, making them unsuitable for magnetorquer-only architectures. For this reason, a less conventional approach, such as the method proposed in [9] is adopted.

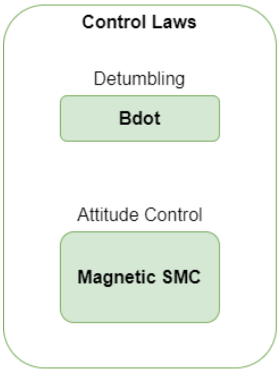

Figure 4: Implemented Control Laws

This Sliding Mode Control (SMC) law, although significantly more complex to implement compared to standard controllers, enables effective attitude control of CubeSats using only magnetorquers, achieving pointing accuracies of about one degree. The selection of this control law stems from the need to address the under-actuation problem and to guarantee high pointing accuracy, particularly for thrust-pointing operations. Since the propulsion system is electric and provides low thrust, effective manoeuvres require maintaining a precise pointing direction over long durations, a condition that this control strategy is specifically designed to satisfy.

2.4. Hardware Modeling

The modelling of mission hardware (Figure 5) was carried out with the objective of reproducing the underlying physics and the typical behaviour of each component.

First, the three magnetorquers were modelled by considering the controller output in terms of magnetic dipole moment. Before being converted into torque, this value is saturated according to the maximum dipole capability

$m_{mag,max}$ of the magnetorquer, defined as in Eq. 1:

$$m_{mag,max} = N\, S\, i_{max} \qquad (1)$$

where N is the number of coil turns, S is the actuator surface and i_{max} is the maximum current. The commanded actuation $\boldsymbol{T}_{\boldsymbol{ctrl}}$, including all hardware constraints, is then computed as in Eq. 2:

$$\boldsymbol{T}_{\boldsymbol{ctrl}} = \boldsymbol{m}_{\boldsymbol{mag}} \times \boldsymbol{B} \qquad (2)$$

where m_{mag} is the actuated magnetic dipole and B is the local magnetic field. Finally, the torque is generated through a Pulse-Width Modulation (PWM) model, used to emulate the square-wave actuation signal.

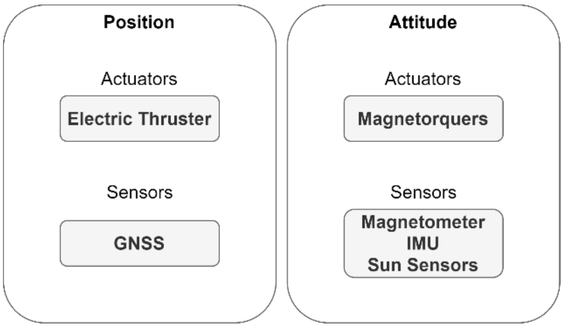

Figure 5: Implemented Hardware

Regarding the thruster, since it is still undergoing characterization, a separate simulation module has been implemented in a parallel branch of the simulator, running concurrently with the standard simulation. This module was developed using GVE and assuming a constant thrust aligned with the orbital velocity vector. The thrust is applied for one quarter of an orbit, repeated over multiple orbits at the same manoeuvre locations, thereby emulating a low-thrust apogee-raising manoeuvre. For attitude purposes, once a maximum allowable misalignment between the thruster and the satellite's centre of mass was defined at system level, an associated attitude disturbance torque vector was considered.

Finally, sensors have been modelled using a prediction state with applied white noise and bias. The disturbance values were taken from the component datasheets and can be updated following laboratory characterization. Measurements and predictions are then combined in a standard Extended Kalman Filter, providing the current estimates of attitude and position.

3. Project Logistics and Programmatics

The project involved, in terms of voluntary work, a dozen students with different engineering backgrounds (aerospace, mechanical, computer science and electronics) and different academic levels (from bachelor's to PhD students). For the high-level management of the project, three members of the team were selected, based on their prior experience, to supervise the individual GNC blocks. A PhD student was responsible for the system-level coordination, organising the simulation framework and maintaining traceability of all updates. The remaining group members then contributed to the detailed subsystem blocks according to their expressed preferences.

From a managerial and programmatic perspective, the development of the simulator in its current form required approximately six months of work. This effort was distributed across literature review - focusing particularly on non-trivial topics such as orbital dynamics, estimation theory, and control methods - preliminary system design, development of the simulation architecture, and implementation and testing of the algorithms.

4. Results and Open Points

The students involved in the project were able to develop knowledge and skills by applying to a real engineering activity some concepts that are typically encountered only at a theoretical level in classroom. Through this work, they gained experience in modelling within the Matlab/Simulink environment, developed an understanding of the complex physical behaviours inherent to space systems, and acquired a broader perspective on the iterative processes that characterize engineering design. Clearly, this was not a straightforward process: translating theoretical concepts into practical implementations, first as standalone components and later integrating them into a unified simulation framework, is an extremely demanding and articulated task. The complexity further increases when considering the interface between the AOCS and the remaining subsystems, as the design must account for the constraints and drivers imposed by the power generation capabilities, the limited volume and mass of a 3U CubeSat, and the economic limitations of a student-led project.

At technical level, several points of interest and discussion emerged during the development.

The principal open point concerns the use of magnetorquers as the sole actuators for attitude control and pointing. While it is well established that magnetorquers alone are effective for detumbling operations, the problem becomes significantly more challenging when fine and dynamic pointing accuracy is required. To verify the correct behaviour of the algorithms, a parallel simulation was carried out assuming the presence of three reaction wheels with characteristic dimensions suitable for a 3U CubeSat. The results of the full-actuation model show a rapid convergence of the system to the desired state in the state–space plots (Figure 6), thereby confirming the proper functioning of the algorithms.

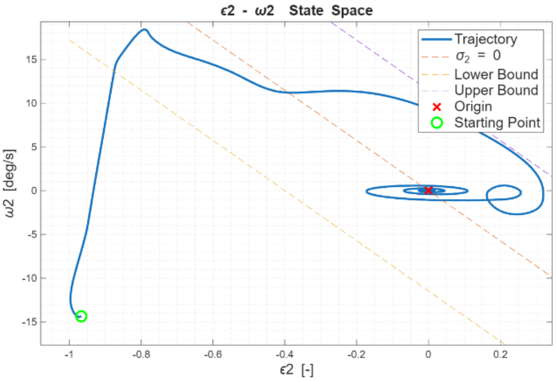

Figure 6: Full model convergence with Reaction Wheels

The discussion therefore remains open regarding the adoption of a hybrid configuration with two magnetorquers and one reaction wheel, which has been identified as a potential candidate for mitigating the under-actuation problem. In addition, an open point concerns the simulation of the Sun Sensor placement, which has so far been modelled but not yet integrated into the full simulator.

Finally, to conclude the preliminary design phase, the validation of the integrated model will necessarily require differentiating the simulation rates, aligning them with the sampling frequencies of the real sensors and actuators. In addition, a Monte Carlo simulation campaign will be carried out to account for system-level uncertainties in the AOCS parameters and in the spacecraft properties.

Acknowledgements

The authors would like to thank the ESA Academy Fly Your Satellite! staff for their support throughout the development of the project, and the Politecnico di Torino university for the logistical and financial support provided.

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