ATTITUDE CONTROL RESEARCH WITH EDUCATIONAL NANOSATELLITES

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Abstract

This paper introduces the three-axis attitude control of the ESAT platform. ESAT is a modular nanosatellite that implements the popular 10x10x10 cm CubeSat standard, designed for hands-on learning at different educational levels as well as professional training. ESAT features the full set of characteristic spacecraft subsystems (power, on-board data handling, attitude control, communications, and payload). The satellite can be disassembled to focus on each subsystem, one at a time, or used all together, and features a flexible ground segment. Courses using the ESAT platform are imparted in our university, as part of the last year of the master's degree in Aerospace engineering, and in other institutions like the ESA Academy. They cover aspects ranging from subsystems design to testing and spacecraft operations. In addition, the platform is used in master's thesis and research activities.

Although the version that is currently being used in the courses allows only one-axis attitude control, the ESAT is in continuous development and two prototypes of the satellite have already been developed that allow three-axis control based on reaction wheels and/or magnetorquers, which is essential for the testing and verification of attitude determination and control algorithms. For this purpose, the ground support equipment has also been updated to be able to carry out the turns in three axes, with the development of new testbeds and a complete magnetic field simulator. The present work aims to show the new three-axis platform designs and its main functionalities.

Keywords

Attitude control, Educational satellite, ESAT, Hands-on training, Nanosatellites.

Acronyms/Abbreviations

ADCS	*Attitude Determination and Control Subsystem*
E-USOC	*Spanish User Support and Operations Centre*
ESAT	*Educational SATellite*
HW	*Hardware*
IMU	*Inertial Measurement Unit*
PCB	*Printed Circuit Board*
PID	*Proportional, Integral, Derivative*
PWM	*Pulse Width Modulation*
SW	*Software*
TC/M	*TeleCommand/TeleMetry*
UPM	*Universidad Politécnica de Madrid*

1. Introduction

The application of active learning methods in engineering training has a huge positive impact [1–4] because of the important practical component of the education. In the context of aerospace engineering, the second cycle of degree and master's programs generally includes subjects with a very technological focus, where practical lessons are fundamental.

In the 2009-2010 academic year, the research group "Ciencias y Operaciones Espaciales", to which belongs the Spanish User Support and Operations Centre (E-USOC) [5], launched several educational innovation activities within the Aerospace engineering degree offered at Universidad Politécnica de Madrid (UPM), implementing practical sessions using benchmark demonstration satellites. At that time, there were few available models in the market and their design offered little flexibility for training activities. These limitations motivated the group to develop a self-designed satellite: the Educational SATellite (ESAT), developed by Theia Space [6], an initiative born at the E-USOC.

ESAT is a modular nanosatellite that implements the popular 10x10x10 cm CubeSat standard, designed for hands-on learning at different educational levels as well as professional training [7]. ESAT features the principal spacecraft subsystems: power, on-board data handling, communications, payload and attitude determination and control (ADCS) systems. The satellite can be disassembled, to focus on each subsystem or used all together, and includes a flexible ground segment. ESAT has been designed so that users can easily expand both its hardware (HW) and software (SW).

Nowadays, ESAT is used in different subjects of the space vehicles intensification of the master's degree in Aerospace engineering at UPM, and in training courses for other institutions like the ESA Academy [8], covering aspects that range from design to testing and spacecraft operations. In addition, the platform is used in master's thesis and research activities. All in all, around 70 ESATs are used in other universities and institutions around the world for teaching or research.

Although the current ESAT version allows only one-axis attitude control [9], the platform is in continuous development to improve its performance and capabilities. As part of this effort, several students have developed their bachelor's and master's degree projects working on the ADCS to achieve a full three-axis attitude control [10]. Two new prototypes have already been developed, offering three-axis attitude control based on reaction wheels and/or magnetorquers, and are being used for testing and verification of ADCS algorithms. These updates include new ground support equipment that allows to carry out the turns in three axes.

The present work aims to introduce the reader the design and main functionalities of the new three-axis ESAT. In section 2, we introduce the preliminary ADCS design. In section 3 and 4, the magnetic and reaction wheels-based prototypes are described, respectively. Section 5 presents the Earth magnetic field simulator and, finally, a brief discussion and conclusions are offered in section 6.

2. Preliminary three-axis control design

The preliminary study of a full three-axis ADCS in ESAT was carried out as part of a bachelor's degree project in 2016. The project focused on HW additions and the identification of required changes to fulfil a complete three-axis ADCS.

2.1. Hardware design and sizing

Since the one-axis version of ESAT already includes sensors to determine its attitude in three axes, the work focused on the design and sizing of the actuators, i.e., the reaction wheels and magnetorquers. We note that the one-axis ESAT controls its attitude around its Z axis, which is aligned with the local gravity vector, using one coaxial reaction wheel and two magnetorquers positioned in two perpendicular axes in a XY plane — a magnetorquer generates a torque perpendicular to its axis.

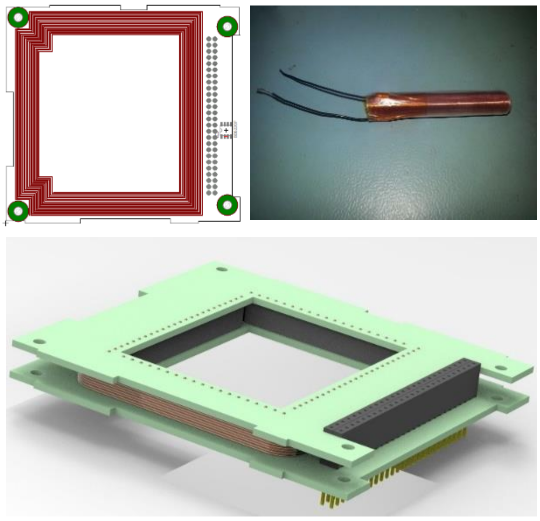

Figure 1. Embedded coil design (top left), manufactured torquerod prototype (top right), and combined air-core/embedded design (bottom).

Therefore, one magnetorquer and, at least, two reaction wheels had to be added.

Different types of magnetorquers: air-core, embedded coil and torquerod, as well as a combined design with air-core and embedded coils were studied; see Figure 1. A trade-off between these possibilities finally suggested that the best option for ESAT was the air-core solution.

Three reaction wheels were also designed to meet the requirements of a three-axis control, including the sizing and selection of Brush-Less Direct Current motors and tachometers.

2.2. Manufacturing, integration, and ground equipment

Different magnetorquers prototypes were manufactured and tested in this project. The integration process, on the other hand, must meet the geometric constraints of the 1U CubeSat and Printed Circuit Board (PCB)/104 standards, and provide a suitable mass distribution. Figure 2 shows two examples of integration proposals: the left optimizes the integration process and the right the mass and the prize.

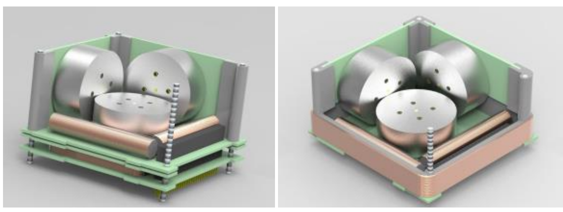

Figure 2. ADCS configurations with different HW.

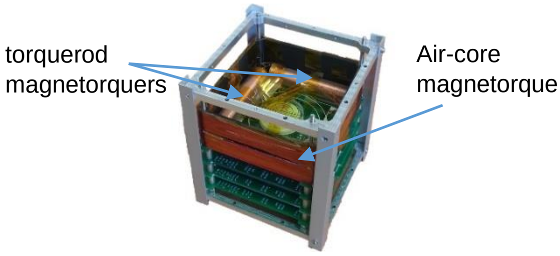

Figure 3. Three-axis magnetic controlled ESAT prototype.

The project was finished with a preliminary study of possible ways to develop a low-cost three-axis testbed for ground tests. This study has been continued in the following years and is still in development.

3. Magnetic three-axis ADCS implementation

With the preliminary design completed, the next step was the implementation of magnetic control and the materialization of the first three-axis controlled ESAT prototype. This prototype, developed during a master's thesis in 2018, added the third magnetorquer, an air core one, and relocated the other two due to geometrical constraints; see Figure 3.

To finalize the development, the complete determination and control cycle was implemented, including sensor reading, attitude estimation, error analysis, control laws definition and actuators commanding.

3.1. Attitude determination and sensors

This prototype was equipped with a three-axis gyroscope, an accelerometer, and a magnetometer. The signals were calibrated to eliminate the bias and a digital low pass filter was applied to reduce noise.

Considering the educational purpose of the satellite, different determination algorithms using different combinations of sensors were implemented: the TRIAD and Q-methods, and the integration of the gyroscopes [10]. In practical sessions, this allowed the student to discover when each method is more suitable, and the numerical problems associated with each of them.

3.2. Control laws

The magnetic three-axis prototype implemented a configuration based on a quaternion feedback schema and a Proportional, Integral, Derivative (PID) control law with the magnetorquers commanded through a Pulse Width Modulation (PWM) signal. Again, a detumbling B-dot

Figure 4. Three-axis magnetic-controlled ESAT and testbed prototype.

control law was also included for educational purposes.

3.3. Communications, ground segment and test facility

Telemetry (TM) and telecommand (TC) definitions followed industrial standards; TM and TC packages complied with the 'Consultative Committee for Space Data Systems' space packet protocol standard. Furthermore, the ground segment data base was defined through the 'eXtensible Markup Language Telemetric and Command Exchange' format.

The master's thesis also included some improvements in the three-axis testbed. In particular, the mass balancing system required to minimize the effect of gravity in ground tests incorporated more stable counterweights and rods; see Figure 4.

4. Three-axis ADCS implementation based on reaction wheels

As a natural extension of the work described above, a new reaction wheels-based ADCS was developed in a subsequent master's thesis.

4.1. Design

The first step of the process was to find the new components needed to achieve the desirable performance, constrained by the available space that ESAT provides to integrate them in its new configuration. In addition, a market search was carried out to study the state of the art and to check if there was any Commercial Off-The-Shelf platform that could be used. During this preliminary phase, simulations of the satellite on the testbed were implemented in MATLAB to have a first estimate of the main parameters that define the design.

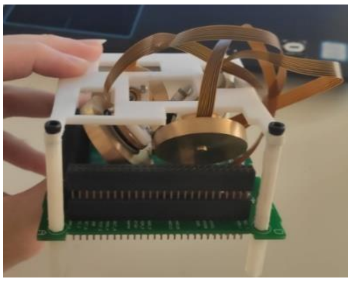

Figure 5. Reaction wheels based ADCS before being integrated in the ESAT.

The detailed design was divided according to HW and SW. The HW design consisted of choosing the motors as well as designing, manufacturing, and assembling a new PCB that included the electronic components for controlling these motors. It was also needed to design the reaction wheels, the wheel-motor coupling and the optimization of wheel's mass, inertia, and spatial arrangement. Figure 5 and Figure 6 show the new ADCS subsystem separately and integrated in the ESAT.

Regarding SW design, the QUEST attitude determination algorithm was added and a PID controller was implemented using modified Rodrigues parameters [11] as control variables. All TM and TC necessary for the satellite control were added, and a graphical user interface was designed.

4.2. Testbed

To analyze the behavior of the ADCS prototype, a new testbed was designed; see Figure 7. This testbed included automatic movement of the masses to reposition the center of gravity by means of stepper motors and an Inertial Measurement Unit (IMU) was added to facilitate the centering process.

Figure 6. Reaction wheels based ADCS mounted on ESAT.

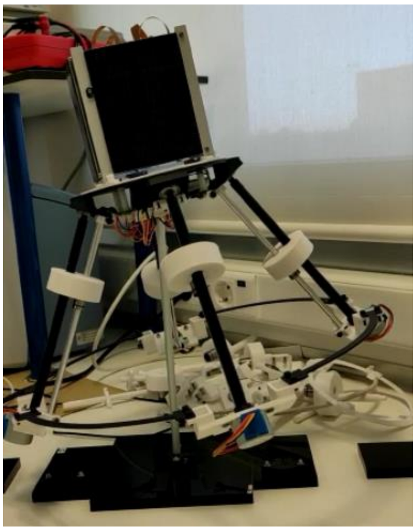

Figure 7. Testbed with automatic reposition of the center of gravity.

This new equipment will also be the starting point for future work of other students. Improvements could be applied for a better location and reposition of the center of gravity as well as for the determination of the inertial matrix. The system could also be adapted to be mounted on an air bearing.

5. Earth magnetic field simulator

The development of new ground support equipment for ESAT also offers great opportunities for students. A complete magnetic field simulator was developed as a bachelor's degree project by using the Helmholtz Coils concept. A structure of three pairs of coils, one per coordinate axis, can generate an orientable magnetic field of adjustable intensity. This type of installation is popular in the space sector for satellite's testing, like the ESA's Magnetic Field Simulation Facility.

5.1. Design and manufacturing

The basic requirements for the simulator were its size and the strength of the magnetic field. The interior space had to fit the ESAT and the different testbeds that had been developed. Regarding the intensity of the magnetic field, it had to be strong enough so that the ESAT would be able to turn overcoming the friction of the turntable by using its magnetorquers.

Having this into account, a CAD program was used to develop the model that afterwards was manufactured using a CNC machine and a 3D-printer as main tools. The body of the coils was milled in wood because of being a non-ferromagnetic material while the joint parts where 3D-printed in PLA. This manufacturing technique makes it possible to design very specific and adaptable parts while the material is resistant enough and non-ferromagnetic.

5.2. Simulator control

The intensity and direction of the magnetic field were controlled using a PID algorithm implemented in an Arduino board. Each coil was connected to a driver that, depending on the PWM signal received, adjusted the power with which the coils were being fed. The setpoint of the system was sent to Arduino from MATLAB through serial communication. The actual magnetic field was measured using an IMU placed in the center of the simulator. This unit was mounted in a bigger board with other electronic components that interfere with the measurements, so calibrating it prior to installation was critical for the proper functioning of the system. With the setpoint and the real measurement, the controller calculated the PWM to be sent to the drivers to adjust the amperage of the coils to generate the desired magnetic field.

A MATLAB-based user interface app was also developed. This app allowed the user to monitor the simulator in real time, set fixed values or program variable magnetic fields as rotating ones and save all the data generated during trials.

5.3. Test and integration with ESAT

The uniformity of the magnetic field was studied by mapping its intensity when a fixed setpoint was commanded. It was proved that the central region of the simulator, where the ESAT would be placed, had a field with irregularities of less than 2.5% with respect to the commanded magnitude.

After several minutes on, the electric resistance of the coils starts to change because they heat up and this could cause undesired variations of the magnetic field. It was tested that the PID successfully counteracted this circumstance.

Once the quality of the magnetic field generated was ensured, the ESAT mounted on the one-axis turntable was tested in the simulator; see Figure 8. The satellite was commanded to keep a certain angle with the magnetic field, and, at the same time, the simulator was programmed to generate a magnetic field whose direction would rotate while being contained in a plane parallel to the ESAT turntable base. The result of the test was successful and the ESAT revolved around its axis following the magnetic field using its magnetorquers as actuators.

Figure 8. ESAT inside the Earth magnetic field simulator on the one-axis turntable.

6. Discussion and conclusions

The new designs and prototypes of the three-axis ESAT platform and its ground support equipment have been presented. These improvements have been carried out by several students through bachelor's and master's degree projects.

These works have allowed students to be involved in real projects, applying basic engineering knowledge as design and manufacturing. They have acquired a very broad view of the different subsystems that compose the satellite and how they relate to each other. In addition, students have gained a better understanding on control algorithms and how the satellites use the magnetic field to move and orientate itself.

Acknowledgements

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