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DESIGN OF THE ACTIVE ATTITUDE DETERMINATION AND CONTROL SYSTEM FOR THE E-ST@R CUBESAT

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One of the most limiting factors which affects pico/nano satellites capabilities is the poor accuracy in attitude control. To improve mission performances of this class of satellites, the capability of controlling satellite's attitude shall be enhanced. The paper presents the design, development and verification of the Active Attitude Determination and Control System (A-ADCS) of the E-ST@R Cubesat developed at Politecnico di Torino. The heart of the system is an ARM9 microcontroller that manages the interfaces with sensors, actuators and the on-board computer and performs the control tasks. The attitude manoeuvres are guaranteed by three magnetic torquers that contribute to control the satellite in all mission phases. The satellite attitude is determined elaborating the data provided by a COTS Inertial Measurement Unit, a Magnetometer and the telemetries of the solar panels, used as coarse Sun sensor. Different algorithms have been studied and then implemented on the microprocessor in order to determine the satellite attitude. Robust and optimal techniques have been used for the controller design, while stability and performances of the system are evaluated to choose the best control solution in every mission phase. A mathematical model of the A-ADCS and the external torques acting on the satellite, its dynamics and kinematics, is developed in order to support the design. After the design is evaluated and frozen, a more detailed simulation model is developed. It contains non-ideal sensors and actuators models and more accurate system disturbances models. New numerical simulations permit to evaluate the behaviour of the controller under more realistic mission conditions. This model is the basic element of the Hardware In The Loop (HITL) simulator that is developed to test the A-ADCS hardware (and also the whole satellite). Testing an A-ADCS on Earth poses some issues, due to the difficulties of reproducing real orbit conditions (i.e. apparent sun position, magnetic field, etc). This is especially true in the case of low cost projects, for which complex testing facilities are usually not available. Thanks to a good HITL simulator it is possible to test the system and its "real in orbit" behaviour to a certain grade of accuracy saving money and time for verification. The paper shows the results of the verification of the ADCS by means of the HITL strategy, which are consistent with the expected values.

I. INTRODUCTION

A Cubesat is a type of miniaturized satellite for space research that usually has a volume of one liter (10 cm cube), weighs no more than one kilogram and typically uses commercial off-the-shelf electronic components. The standard 10×10×10 cm basic Cubesat is often called "1U" Cubesat (meaning one unit) but Cubesats are scalable along one axis, so by 1U increments: Cubesats such as a "2U" Cubesat (20×10×10 cm) and a "3U" Cubesat (30×10×10 cm)

have been both built and launched. Since Cubesats are all 10×10 cm (regardless of length) they can all be launched and deployed using a common deployment systems, for example, the Poly-PicoSatellite Orbital Deployer (P-POD).

Taking into account all the launches from June 2003 until July 2012, approximately 80 Cubesats were put into orbit (with alternate fortunes), and only the 33% of them (27 elements, excluding some U.S. military satellites for which has not been possible to find information) were equipped with an active Attitude Determination and Control System. This small number consists of 22 "1U", 3 "2U" and just only 2 "3U".[1]

A detailed analysis of the components used for active ADCS shows that in almost all cases three types of sensors are used: sun sensors, magnetometers and gyroscopes (for some mission they are replaced by GPS receiver); in a few cases horizon sensors and star trackers have also been used but they are usually discarded due to the size and complexity but, above all, because of costs considerably high. With regards to the actuators adopted, also in this case we cannot observe a wide variety of types: magnetic torquers are the most used, in fact, they were chosen for 26 out of 27 Cubesats with active ADCS; in 3 out of these 26 cases they were also used with reaction wheels and only in one case micro-thrusters have been employed as actuators; lastly there is a single Cubesat that used only reaction wheels for attitude control.

Focusing on the "1U" type, the most widespread configuration involves the use only of magnetic actuators, in fact this is the case concerning 17 satellites of 22: in this way is built a configuration that guarantees the possibility of obtaining a good pointing (and in general a proper attitude control) while not increasing significantly cost and complexity of the subsystem.

The "3U" Cubesat is a category not very common at this moment: in fact, in orbit there is/has been a considerable number (about 60) of units of the "1U" type, while the number of 3U type launched is slightly more than 10. Among these, three have been designed by NASA (therefore for obvious differences in the available budget, they cannot be a source of information to design the attitude determination and control system) and most of the remaining have a passive ADCS, in fact only 3% of all Cubesats launched is "3U" system with active ADCS. Accordingly, an active ADCS for this category represents an important innovation and challenge, just because the background is not as wide as the "1U" category.

II. ACTIVE ADCS DESIGN FOR E-ST@R CUBESATS

E-ST@R project[6] is an educational and research program carried out by the STAR (Systems and Technologies for Aerospace Research) team of the DIMEAS (Department of Mechanical and AeroSpace Engineering) at Politecnico di Torino. Aims of the project are the design, the development and the launch of a series of Cubesat called E-ST@R. The project involves students, both graduate and undergraduate, under the supervision of researchers and professors. E-ST@R has been put into orbit by the Vega Launch Vehicle during its maiden flight on February 13th 2012. The E-ST@R program is driven first of all by the relevance that the mission has both for the research and the education purposes, being at the same time constrained by limited budget availability. For these reasons, one of the main objectives of the project is the development of effective and efficient methodologies to support the entire satellite lifecycle. In particular, the main scientific purpose of E-ST@R is the on-orbit verification of a custom A-ADCS based on COTS (Component Off The Shelf) in order to maintain the low costs program constraints.

Fig. I shows the E-ST@R Cubesat at the end of the assembly process and ready for final integration in the P-POD.

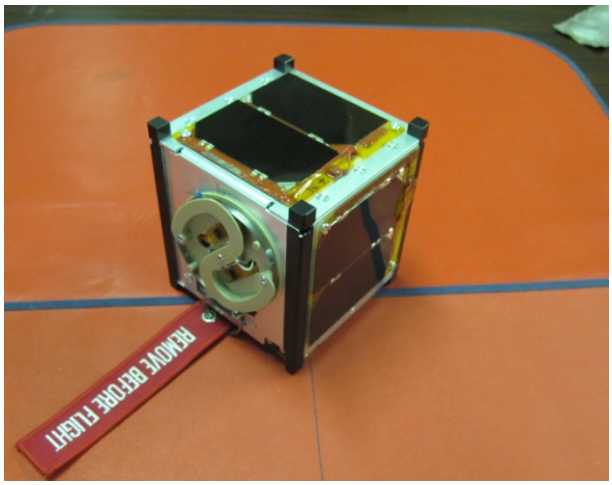

Fig. I: E-ST@R Cubesat

II.I A-ADCS DESIGN

The attitude determination and control subsystem measures and controls the spacecraft's angular orientation. The system must be able to ensure desired antenna pointing (to the nadir) and adequate reorientation when required, so it is necessary an active control system, because the pointing accuracy provided by passive systems is not suitable for this type of mission.

The first step of the A-ADCS design is the analysis of needs and top level (mission) requirements. The functional analysis, made through the functional tree shown in Fig. II, Fig. III, Fig. IV and Fig. V, allows defining the main subsystem function:

- to determine attitude;

- to control attitude (counteracting disturbance torques);
- to communicate data and health-status to OBC (On Board Computer);

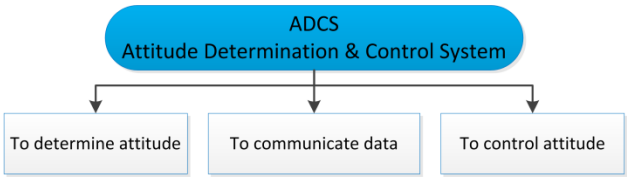

Fig. II: Functional tree (top level) of E-ST@R A-ADCS

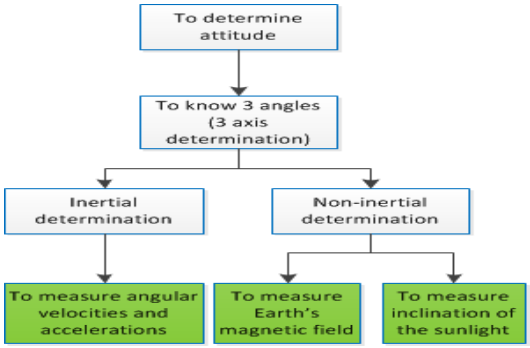

Fig. III: Functional tree (part 1) of E-ST@R A-ADCS

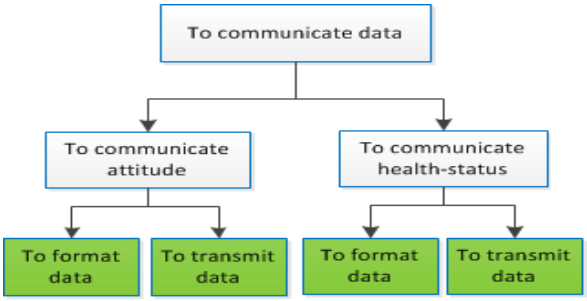

Fig. IV: Functional tree (part 2) of E-ST@R A-ADCS

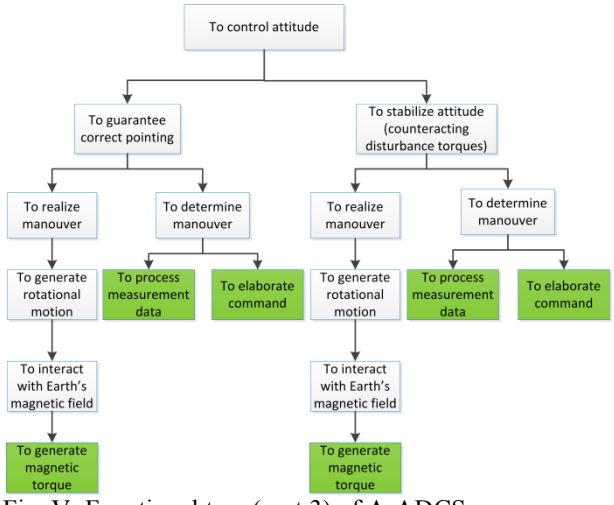

Fig. V: Functional tree (part 3) of A-ADCS

Fig. VI shows the functions/components matrix by means of which all the components of the A-ADCS are chosen.

	Sensors			Actuators	Microprocessor
Components→ Functions↓	IMU	Magnetometers	Solar panels (as coarse sun sensor)	Magnetic torquers	ARM
To measure angular velocities and accelerations	X				
To measure Earth's magnetic field		X			
To measure inclination of the sunlight			X		
To format data					X
To transmit data					X
To process measurement data					X
To elaborate command					X
To generate magnetic torque				X	

Fig. VI: Matrix functions/components of A-ADCS

The blocks scheme of the A-ADCS is shown in Fig. VII: black lines indicate the power connections, red lines indicate the digital data connection, blue lines indicate analogue signals.

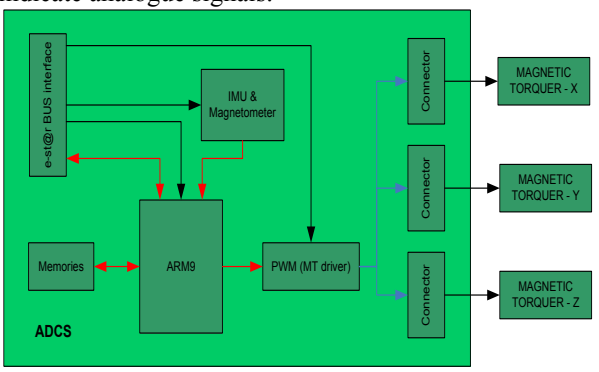

Fig. VII: Blocks scheme of A-ADCS

Moreover, in Fig.VIII the logical interfaces with the other on board subsystem are shown.

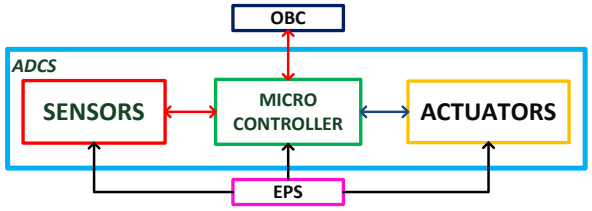

Fig. VIII: A-ADCS interfaces with the other subsystems

A-ADCS Hardware design

The heart of the hardware system is a custom embedded board that hosts the ARM9-RD129 (produced by ELPA s.a.s.) micro-controller, the Inertial Measurement Unit (IMU) and all the electronic circuits to drive the Magnetic Torquers (MT), to amplify signals and to interface the board with the other subsystem through the E-ST@R bus. The used ARM9 I/Os are three serial channels (one only for debug), three timers,

and other general-purpose pins. The USART0 allows the communications with the IMU (Xsens' MT9, with integrated magnetometer) placed near the centre of mass of the satellite and fixed in the top face of the ADCS board. It provides data (with a specific protocol) related to the angular velocities, the linear accelerations and the Earth magnetic field. USART1 allows the communication with the OBC and USART2 is a debug/test line.

The driving circuits for the MT transform the low level/low voltage command signals in output from the microcontroller to the higher level voltage applied to the actuators. The command logic is a Pulse Width Modulation (PWM) and the signals are generated by the three "timer" outputs of the RD129 with appropriate values.

Other electronic circuits are designed to acquire the current (flowing into the MT) data: in particular, these outputs are [0-3.3] V signals and the values are proportional to the current that flows into the MT: in this way it is easy to monitor the power consumption. The microprocessor receives the signals on the GPIO (General Purpose Input Output) pins and the values are put into virtual files, managed by the software.

ADCS Software Design

The Operating System (OS) is Linux Embedded. The software is written in C++ and, after the cross-compiling, the generated files are loaded on the RD129. Moreover, a specific kernel has been developed in order to optimize the microcontroller resources.

The program is structured in three parts:

1. *"inizialization":* all the requested setups are made (USARTs, virtual files, PWM frequency, etc.);
2. *"interface loop"*: it is an infinite loop in which the RD129 acquires sensors and status data and exchanges telemetries and commands with the OBC;
3. *"control loop"*: it is a loop in which telemetries are managed in order to determine the attitude. Then the new commands are computed (according to the control laws) and the PWM values are set for the driving circuits.

More in details, at the beginning of the interface loop the software receives the packets from the OBC, evaluates the message type that could be:

- a command (among "new desired attitude", "update orbital parameters", "switch on/off the subsystems"). In this case all the actions imposed by the command are performed.
- a telemetry (mainly solar panels data). In this case the information is handled in order to be ready for the attitude determination.

At the end of the interface loop, the software gathers and manages the IMU data, the MT telemetries and formats them together with the quaternions values and the time tag, according to a custom protocol, and sends data to OBC.

The outputs control loop are the commands for the magnetic torquers given as percentage of the maximum applicable control, that is the duty cycle. The needed inputs are:

- **time**: held by the processor as date and milliseconds in the Coordinated Universal Time (UTC);
- **magnetic field**: in Body coordinates starting from the magnetometer data;
- **inertial angular velocity**: in Body coordinates given by the IMU;
- **NORAD TLE**: a vector containing orbital parameters;
- $\mathbf{q_d}$: desired attitude, expressed by quaternion;

The main routines developed are briefly summarized hereafter:

- **magf** estimates the satellite orbital position, sun and magnetic field vectors;
- **sole** determines the sun vector from the outputs of solar panels;
- **Svot** compares the measured and the calculated sun vectors;
- **Bvot** compares the measured and the calculated magnetic field vectors
- **detqiniz** evaluates attitude from sun and magnetic field vectors according to the TRIAD algorithms.[8]
- **kalman** implements the Kalman filter on the system outputs (angular velocity and attitude);
- **qvot** makes voting between calculated, measured and filtered attitude in order to choose the best determination;
- **controllosat** computes the commands that shall be applied;
- **torquers** calculates the PWM duty-cycle for each MT, according to the calculated commands.

III. ALGORITHMS IN THE LOOP SIMULATION FOR THE CONTROLLER DESIGN

The mathematical model of the satellite has been developed according to the dynamics and kinematics laws reported in this section.

The general dynamic law is

$$\dot{h}_b + \omega_b \times h_b = T_b \qquad [1]$$

where h_b is the momentum vector, w_b the angular velocity and T_b the sum of the active torques on the satellite. The angular acceleration results, if there are no internal moving parts:

$$\dot{\omega}_{ib} = I^{-1}\left(T_b - \omega_{ib} \times I\omega_{ib}\right) \quad [2]$$

There are many sources that provoke torques acting on the satellite during its orbital life and attempt to change its attitude. The main disturbance torques on a satellite are due to interaction of the satellite with the Earth's gravity field, Earth's magnetic field, solar wind and the atmosphere. However, not all these factors equally affect satellite attitude; for this reason, taking into account the E-ST@R orbit and the related environment, only the gravity gradient torques, the atmospheric torques and the magnetic torques are considered.

$$\begin{aligned} T_g &= -3\omega_o^2 \hat{r} \times I\hat{r} \\ T_a &= r_{cp} \times \left(\frac{1}{2}\rho V^2 C_D S\hat{v}\right) \\ T_m &= m \times B \end{aligned} \quad [3]$$

where T_g is the gravity gradient torque vector, I is the inertia matrix, ω_o is the orbit rate, $\hat{r}$ is the unit vector along the local vertical passing through the satellite center of mass, T_a is the atmospheric torque vector, r_{cp} is the distance vector between the center of mass and the center of pressure of the satellite, ρ is the atmosphere density, V is the satellite speed, C_D is the drag coefficient, S is the spacecraft projected area normal to $\hat{v}$, T_m is the magnetic torque vector, m is the dipole moment vector and B is the Earth Magnetic Field (EMF) vector.

Moreover, to complete a first basic step of the design, the orbit and the EMF models are added. This configuration allows investigating the problem of the control, evaluating the possible laws and techniques and verifying the performances and the strategies.

A theoretical model, as the simple magnetic dipole model, is not sufficient to properly model the EMF. It was therefore decided to rely on model *WMM* (World Magnetic field Model) developed by the National Geophysical Data Center of the NOAA (National Oceanic and Atmospheric Administration) which is released every five years: it takes into account with good approximation the variations of the geomagnetic field using linear approximations based on observations made in previous years and extrapolated for the next five years[2].

III.I CONTROL DESIGN

The problem of in-orbit attitude control is quite complex: in fact, the control requirements vary with the vehicle's motion characteristics and require different actuators and sensors usage. The functional implementation of the control has been made from Wiśniewski[3] in which the problem is solved as follows.

Detumbling phase.[7]

After the satellite has been released by the launcher, it has a high initial angular velocity with respect to the inertial frame so it is really difficult to evaluate the satellite attitude. For this reason the E-ST@R angular velocities must be first reduced: particularly the kinetic energy has to be dumped. This control mode is referred to as "detumbling mode" and ends when the angular velocity of the body frames w.r.t. the inertial frame is less than 0.002 rad/s around each axis.

The angular velocity feedback controller law during the detumbling phase is:

$$\mathbf{m} = \mathbf{K}_{\det}\omega_{ib}^{b} \times B \quad [4]$$

where K_{det} is a positive constant matrix, B is the Earth magnetic field and ω_{ib} is the angular velocity of the body frame w.r.t. the inertial frame.

Stabilization phase

After the detumbling phase has been completed, the satellite is stabilized, but its attitude will be random and it will oscillate around an angle that depends on the initial conditions. The body frame, which is the orthogonal system centred in the body's centre of mass and fixed with the body itself, has still to be aligned with the orbital frame (the orbital frame is defined as that frame centred in the centre of the Earth, with the x-axis x_o directed towards the direction of motion, the z-axis directed toward the centre of Earth and the y-axis completing the right hand system) to ensure that the satellite reaches the desired pointing. This goal can be reached by means of the so-called "stabilization mode". The stabilization controller has to dump the oscillation (and eventually to resist the disturbance torque) to achieve the required pointing accuracy.

A Linear Quadratic Regulator (LQR) has been designed to control the attitude of the satellite in the stabilization phase, when E-ST@R shall point its dipole antenna to the nadir. The linear time variant model has been defined in order to apply the LQR theory, as per equation [5].

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) \quad [5]$$

where x(t) is the state variables vector $[q_1,q_2,q_3,q_1,q_2,q_3]$, u(t) is the control inputs vector $[m_x,m_y,m_z]$, A and B are the matrices defined in [7] and [8].

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -4\sigma_x\omega_0^2 & 0 & 0 & 0 & 0 & (1-\sigma_x)\omega_0 \\ 0 & -3\sigma_y\omega_0^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\sigma_z\omega_0^2 & (1-\sigma_z)\omega_0 & 0 & 0 \end{bmatrix} \quad [6]$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{2I_x} B_z^0 & -\frac{1}{2} B_y^0 \\ -\frac{1}{2I_y} B_z^0 & 0 & \frac{1}{2I_y} B_x^0 \\ \frac{1}{2I_z} B_y^0 & \frac{1}{2I_z} B_x^0 & 0 \end{bmatrix} \quad [7]$$

where $\sigma_x=(I_y-I_z)/I_x$, $\sigma_y=(I_x-I_z)/I_y$ and $\sigma_z=(I_y-I_x)/I_z$.
The solution of the problem is:

$$u(t) = -K_{LQR}(t)x(t) = R^{-1}B^T P(t) \quad [8]$$

where K_{LQR} is the control matrix computed by solving the Riccati Equation[10]:

$$\dot{P} = -P(t)A - A^T P(t) - Q + P(t)BR^{-1}BP(t) \quad [9]$$

where Q, R are weight matrices, defined in order to minimize the consumption due to the usage of the MTs rather than have an higher accuracy and have a faster achievement of the desired attitude.

III.II FINAL CONFIGURATION

In order to reach the best solution for the control design and verify the features of the whole system a more complex mathematical model is developed. In particular, models have been added for:

- inertial measurement unit (simulated with gaussian noise and with a specific model);
- magnetometer (simulated with gaussian noise and a specific model);
- Magnetic Torquers;
- Kalman filter.

In order to verify how the control acts, a Simulink model has been built and it is shown in Fig. IX.

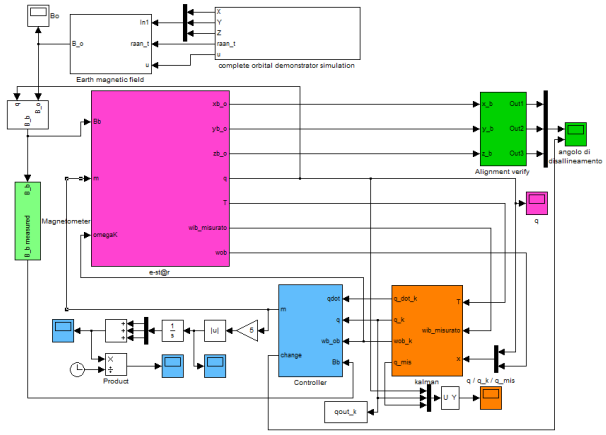

Fig. IX: Matlab/Simulink© model

Some simulations have been made and their results are here presented. Fig. X shows the angular velocities tending to zero after detumbling phase that is completed after 9700 seconds. The stabilization phase brings the satellite to reach the desired attitude (with an accuracy of 0.05 rad), as shown in Fig. XI.

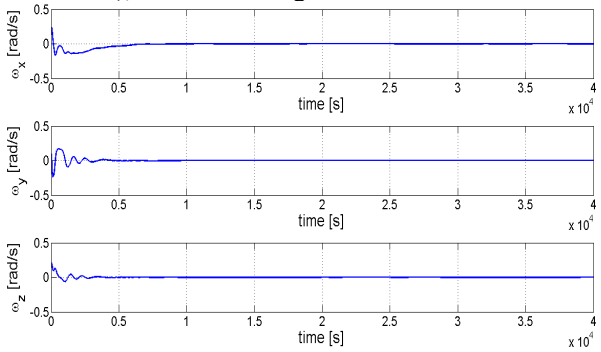

Fig. X: Angular velocity.

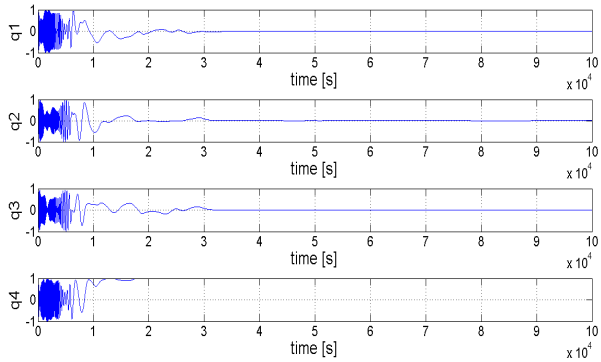

Fig. XI: Attitude.

In Fig.XII the evolution of the Earth magnetic field measured with an appropriate model of magnetometer and the percent error between measured and calculated are shown.

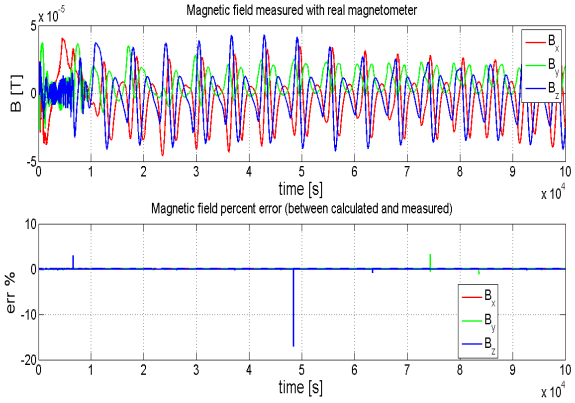

Fig. XII: Earth Magnetic Field.

Fig. XIII shows the dipole moment required to MT: it is possible to note that they are much more used in the detumbling w.r.t. the stabilization phase.

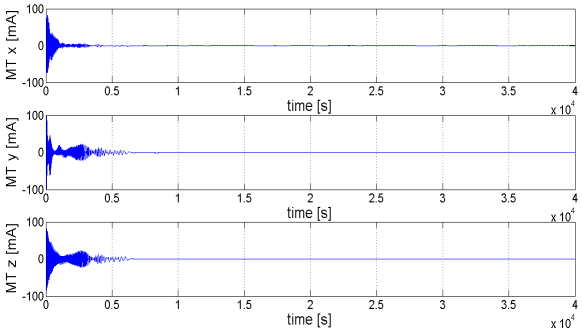

Fig. XIII: Currents flowing into MT.

IV. VERIFICATION CAMPAIGN FOR A-ADCS FUNCTION WITH HARDWARE IN THE LOOP SIMULATIONS

In general, the main objective of the HITL simulator is to have a simulation platform for the functional verification of embedded systems. In the E-ST@R program[5], HITL simulations carry out the verification of many functional and operational requirements, in particular, the following macro-verifications can be accomplished:

- Transmissions and receptions of telemetry and commands
- Power consumption
- Batteries charging and discharging
- Attitude determination and control

Within this paper, the interest is mainly focused on the last point.

Briefly, the Hardware In the Loop technique is particularly useful when dealing with system developed for hardly reproducible environments, as open space. The only possible alternative to a HITL simulation is to reproduce the environmental conditions that the system will experience during its operative life. This is normally more expensive and more difficult to perform than a HITL simulation.

For example, in order to test the A-ADCS of E-ST@R in the laboratory without HITL simulation, 1) the apparent sun position, 2) the thermo-vacuum environment, 3) the magnetic field, 4) the micro gravity condition, and 5) the orbital speed should have been physically reproduced and that requests big resources, expensive facilities and high costs, not sustainable for a students' initiative.

Moreover, HITL simulation includes electrical emulation of sensors and actuators. These emulations act as the interface between the simulator and the embedded system under test. The output value of each sensor is computed by the simulator and is read by the embedded system under test. In the same way, the embedded system gives actuator control signals and sends them to the simulator.

More in general, every simulated system shall behave as the real one not only for the numerical or physical outputs but also for the type of interfacing with the other tested parts or systems. It is quite clear the importance of the modelling activity: the more a model is accurate the more the real behaviour is well reproduced. But, at the same time, it is necessary to maintain a low cost simulation from the computational point of view, so in many cases one of the hard efforts is to identify exactly the features that actually bear on the model in order to make a satisfactory result.

IV.I SIMULATOR FEATURES

To verify the system via HITL simulation some main "actors" can be identified, as shown in Fig. XIV.

Test object: the E-ST@R Cubesat composed by EPS (Electrical Power System - electronic boards and batteries packs), OBC, COMSYS (COMmunication SYStems - electronic board and antenna) and ADCS board; real sensors and actuators are electrically connected to the system but only to verify their power consumption.

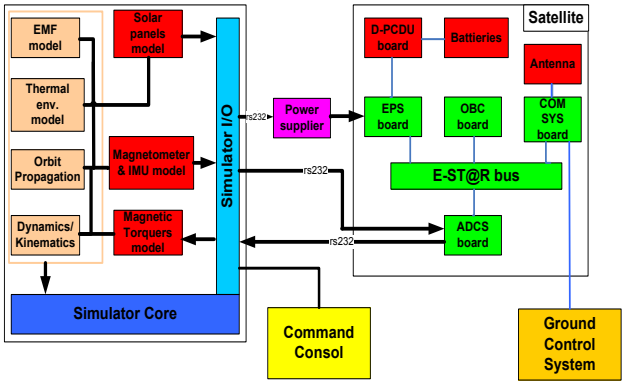

Fig. XIV: E-ST@R HITL simulator blocks scheme

Simulated Satellite equipment: 1) Solar panels and related thermal sensors of EPS. The mathematical model of solar panels has been developed and, using the simulated information about sun position, satellite attitude and thermal conditions, the voltages and the currents supplied by each panel are computed. These values are used to set the power suppliers that are connected to the EPS board to supply satellite with the desired voltages and currents; 2) IMU; and 3) the MTs. Mathematical and stochastic models of the gyroscopes and the tri-axial magnetometer are included in the simulator. The models of the MT are used to calculate the magnetic dipole that, with the Earth Magnetic Field (EMF) simulated data, generates the control torque.

Simulated Orbital condition: the orbital condition simulation regards the models of: 1) the satellite orbital position, in order to know the position of E-ST@R centre of mass at all times; 2) the thermal flows on the satellite; 3) the EMF; and 4) the dynamics and kinematics of the satellite. Moreover, to know the orbital position is necessary for obtaining the local sun

vector and, together with the simulated magnetometer, the local magnetic field. The sun vector is useful to calculate the thermal flows and the temperatures on solar panels.

Simulator interfaces play an important role in HITL simulation because they have to guarantee any type of communications between the simulator and the satellite. The communication between the simulator and the programmable Power Packs is made through a RS232 serial port providing the correct values of currents and voltages to the solar panels connectors on the PCDU (Power Control and Distribution Unit) of onboard EPS, as if the five solar panels were in orbit. The communication to and from the A-ADCS ARM9 is made with a serial cable; this communication is also used for debug purposes.

The physical interfaces of the E-ST@R HITL simulation test bench are:

- Channel 0 connects simulation PC to MAX232 and MAX232 to ARM9 debug port on A-ADCS board. Thanks to this link, the A-ADCS board returns the PWM (Pulse Width Modulation) commands. Moreover, using this channel, the operator can check the correct activation of ARM9 and monitor in real time the A-ADCS behaviour.
- Channel 1 connects simulation PC to Power Pack N1. Simulation software transmits solar panels currents and voltages to set Power Pack N1 in order to simulate solar panels +x, +y, -y. The three Power Pack outputs are connected directly to the six pins connectors of onboard PCDU.
- Channel 2 connects simulation PC to Power Pack N2. Simulation software transmits solar panels currents and voltages to Power Pack N2 in order to simulate solar panels +z and -z . Two of the three Power Pack outputs are connected directly to the six pins connectors of onboard PCDU.
- Channel 3 connects simulation PC to IMU on A-ADCS board. Simulation software transmits simulated IMU row data to A-ADCS board in terms of angular velocities and local Earth magnetic field, formatted as specified in the IMU data-sheets.

Simulator core is the most relevant part of the simulator and it is composed by a laptop with Linux as OS. In order to guarantee as much as possible the simulator Real Time activities, all the unused functionalities of the OS are inhibited. It is able to manage all the requested interfaces and it allows the operator to interact with the simulator using the Control Console (keyboard and mouse) and check data on the screen.

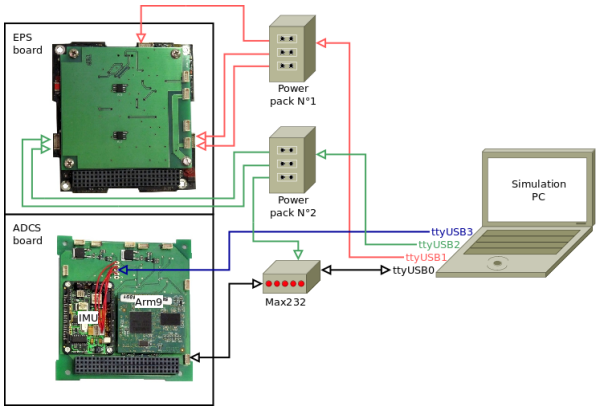

Fig. XV: interfaces E-ST@R Cubesat and simulator

The laptop operates as the simulator core when a special program (written in C++) runs. This program is able to: 1) schedule all tasks according to priorities and time and logical sequence; 2) manage the logical interfaces with the test-object (E-ST@R); 3) visualize and save all the information related to the running simulation.

IV.II SIMULATION DESCRIPTION

How does the simulator work? The simulator receives the PWM commands calculated by A-ADCS board in terms of duty cycles (minimum value 0, maximum value 1000) through Channel 0.

From these data the simulation software calculates the applied voltages, the currents flowing into the MT, and then the generated dipole moment is determined.

The dipole moment together with EMF simulation (and the magnetometer model acquisitions) causes the magnetic control torque value, that enters in the dynamic and kinematic simulation models in order to obtain the values of the angular velocities about the satellite body axes w.r.t. the inertial reference frame.

The angular velocities values (and the magnetometers values) are converted in data strings in order to simulate the real behaviour of the IMU and are transmitted to A-ADCS board through Channel 3.

In a similar way, the simulation software determines heat fluxes on each face (according to satellite attitude) and, consequently, temperatures on each solar panel. Heat fluxes and temperatures enter in the solar cells model in order to get the power generated by solar panels in terms of voltage and current. These information are transmitted to the two 3-channels power supply units by serial communication through Channels 1 and 2. Power suppliers provide voltages and currents to the PCDU. The OBC acquires the real telemetry, saves it and passes the solar panels' values to the A-ADCS in order to calculate the "real" sun vector. Sun vector, Earth Magnetic Field and angular velocities data allow to determine the satellite attitude, used by the A-ADCS board to control the attitude of the satellite

computing the new PWM duty cycles and finally sending them back to the simulation PC.

IV.III TESTS AND RESULTS

In order to carry out the HITL simulation, the needed equipment includes the support equipment for the Cubesat, the Cubesat itself and the GCS (Ground Control Station).

HITL verification conditions are those of STAR laboratory (at Politecnico di Torino) in terms of temperature (about 25°), atmospheric pressure (about 985 hPa), and air humidity (45%).

Parameters to be analysed

In order to verify the correct behaviour of the A-ADCS of the satellite, the remarkable telemetry parameters shall be analysed, in particular:

- Solar panels' voltages, currents, and temperatures;
- Quaternions;
- Angular velocities;
- EMF;
- Real MT consumptions in terms of current;

Data analysis is mainly performed by Matlab©, following this procedure:

1. Data are imported from
    - SD memory card (on-board the satellite)
    - GCS log files
    - Simulator log files
2. Data are handled, converted and interpreted.
3. The most meaningful variables are chosen and the respective graphs are plotted.
4. The graphs are then evaluated.

Analysis of the data

After the detumbling phase, the satellite angular velocities remain constant w.r.t. the inertial frame, therefore the satellite is not spinning. In Fig. XVI it is possible to notice that the satellite's angular velocities are close to 0 rad/s.

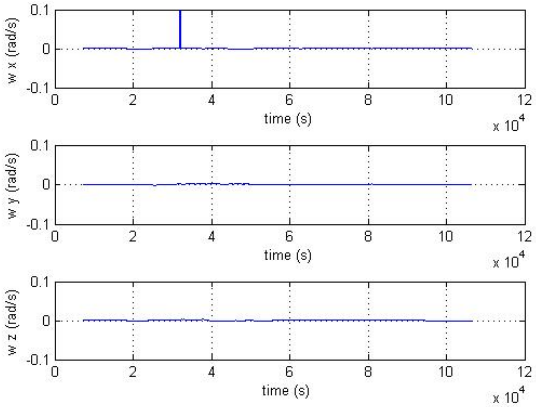

Fig. XVI: Angular velocity (HITL).

Fig. XVII shows that the desired attitude (antenna pointing to the ground, reference quaternion [0 0 0 1]) is achieved with the expected accuracy. The attitude is well determinated (using solar panels, IMU and Magnetometer data that are provided by the simulator) by algorithms and Kalman filter in the ADCS software. Within the first day of the mission the desired pointing is achieved and within a few hours from the ejection from LV (Launch Vehicle) it can be reached a pointing that ensure communications and, in particular, the pointing error measured at the end of the test is less the 8°.

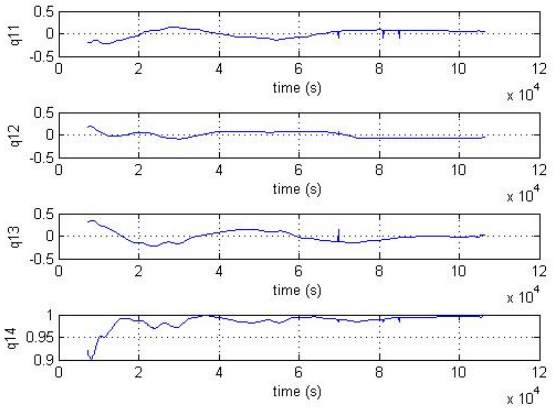

Fig. XVII: Attitude (HITL).

The recording of MT data consumption begins when the detumbling phase is already complete (on GCS log files), thus Fig. XVIII shows small currents that flow into the MTs in order to achieve accurately the desired attitude. In fact, data are recorded when the detumbling phase has been successfully completed and only very small manoeuvres are requested to reach the correct attitude (antenna pointing to the Earth)

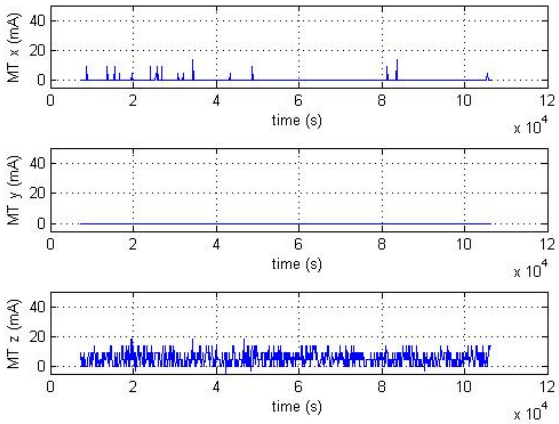

Fig. XVIII: Currents flowing into MT (HITL).

In Fig. XIX simulated earth magnetic field is shown. This graph is useful in order to validate the model of EMF developed for the simulator. The plotted data are consistent w.r.t. the expected values.

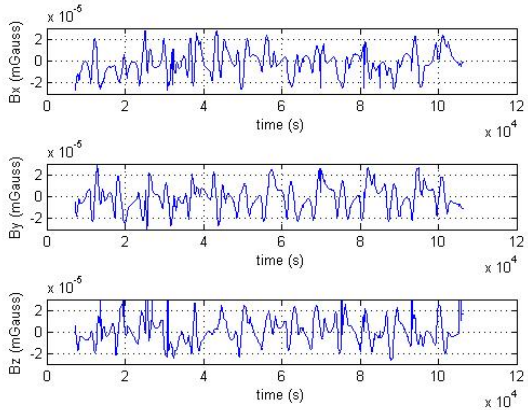

Fig. XIX: Earth Magnetic field (HITL).

V. CONCLUSIONS

The paper describes the design, the development, the integration and the verification of the Active Attitude Determination and Control of E-ST@R Cubesat.

The design process and methodologies are explained, and the main features of hardware and software are highlighted. The controller project is developed according to the most popular techniques used in Cubesats with an A-ADCS system based on magnetic actuators. The design validation is carried out through mathematical models with different degrees of detail and accuracy, taking into account the product life cycle phases. Algorithm In The Loop simulations are performed to confirm the capabilities of the controller and set its gains in a proper manner. The first results show the good performances of the system in the detumbling phase as well as in the stabilization phase.

Hardware In The Loop simulation are also led in order to verify and validate the behaviour of the A-ADCS on the real hardware, in particular paying attention to the microcontroller activities. A complete description of the HITL simulator developed by the STAR team is presented and the results of the simulations related to the A-ADCS of E-ST@R are shown and discussed.

E-ST@R was the first Cubesat built at Politecnico di Torino. Other two satellites (one 1U cubesat named e-st@r-2, and a 3U Cubesat named 3STAR[4,11]) are now under development at the STAR lab and both include an active ADCS similar to the one described in the paper. Updates on hardware and software are now implementing in order to improve the performance of the determination and control tasks and the reliability of the A-ADCS system: in particular, new controller hypotheses are evaluated (i.e. adaptive control)

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