ATTITUDE CONTROL SYSTEM FOR NANOSATELLITES OF CUBESAT TYPE

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ABSTRACT

The INSSET Institute of Saint-Quentin is being involved for several years in a project to design all the modules to make a nano-satellite of cubesat type with objective to launch it into orbit in 2016. Generally, the missions require a knowledge or/and a correction of the satellite orientation relative to Earth. Indeed, many events can cause a gravity centre modification (during the solar panels output or during the ejection phase for example). These actions have for effect to give to the satellite an unwanted rotation on one or more given axis, which can be incompatible with the mission objectives. So it becomes necessary to be able to correct this attitude and to eliminate these effects of parasites rotations. This function is supported by a system named "ADCS" (Attitude Determination and Control System).

1 INTRODUCTION

The INSSET of Saint-Quentin [1] includes a Master degree in the field of embedded systems based on training projects (30% of ECTS credits) in which student groups contribute to develop solutions that meet the needs of industrials or research laboratories. In recent years, we promote the development of plat-forms that have the advantage of dealing with more complex problems along several years.

To date, we are working on three different platforms:

- PRO.MO.CO composed of a set of mobile robots built from autonomous software and hardware modules (smart sensors and actuators communicating on a bus) [2].
- The GENSO ground station to decode telemetry data of amateur and scientific satellites, controllable remotely through the Internet protocol [3] [4].
- The cubesat [5] project (for which this article is the subject) based on the design and development of the wholeness of the modules constituting a nanosatellite (1W, 1dm3, 1kg). The satellite payload will be constituted of various scientific experiments, such as a low cost module enabling the transmission of video images to ground stations [6] via the radio transponder and of our new ADCS subsystem.

2 PROBLEMATIC

A cubesat is a nanosatellite in the shape of cube, of side 10 centimetres (1 litre volume) composed of CoTs electronic components. It was defined by Polytechnic University of California and Stanford University (United States) to allow universities of the whole world, the launch in space of scientific experiments in a reduced cost. More than hundred satellites of this type were launched or are in development (2009 numbers).

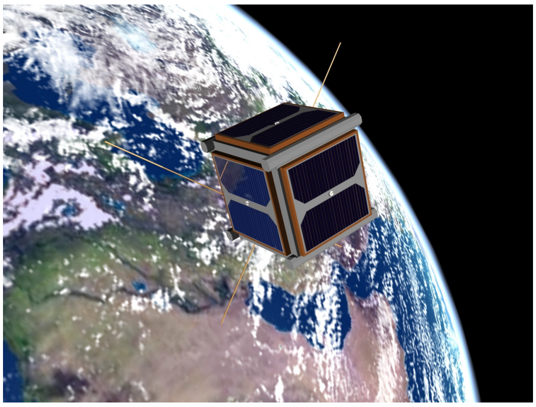

Figure 1. AAU Cubesat (Aalborg University - Denmark)

Among the numerous scientific applications that we can find in cubesats, some require a specific position relative to Earth, for example, for the taking of photos, the orientation of the radio transmission aerials or solar panels, etc. To answer this problem, the INSSET therefore intends to develop an Attitude Control System (ACS).

The Attitude Control System is the set of equipments and algorithms implemented on a spacecraft (artificial satellite, space probe, space station or manned spacecraft) to enable precise control of its attitude, that is to say, its orientation in space around its center of gravity.
The Attitude Control is distinguished from the Orbit Control which is to control the position (and derivatives) from the center of gravity of the spacecraft in space.
The cubesats typically have a unique attitude control (ACS), but certain satellites such as geostationary satellites also have an orbit control system (AOCS).

The Attitude Control, due to the diversity and the complexity of the engineering disciplines which must be implemented, became a full discipline practised by some specialists working for the major actors in the spatial domain or in Universities.
This domain appeals to the mechanics, physics, automatics and of course, mathematics (algebra mainly) [7] [8].
An ACS can be divided into three main parts:
- ➢ Current attitude determination of the satellite via its sensors.
- ➢ Calculation of changes to make to the satellite attitude to reach the desired position (onboard calculator).
- ➢ Changing the satellite attitude through its actuators.

2.1 Determination of satellite attitude

In order to efficiently change the attitude of a satellite, it is necessary to know its position in space and its current orientation.
To do this, it is possible to use different sensors.

- ➢ Optical sensors: This sensor type is essentially based on a view field measurement. Among these, we can found the stellar sensors, which take a photograph of an area of the sky through which it is then possible, using an onboard catalog, to estimate the satellite attitude with an accuracy up to the sub-arcsecond; Earth sensors which are sensitive to the infrared emission of the terrestrial disk and can detect the earth's horizon with an accuracy of a few arc-minutes; Or even the solar sensors that detects the satellite attitude relative to the sun, which with its diameter of half a degree from Earth, is a simple attitude reference and allowing to obtain a resolution better than arc-minute.
- ➢ Inertial sensors: In this sensors family is mainly found the gyroscopes, which offer us the possibility to know the satellite's rotational speeds, and the accelerometers that enable to

know the satellite's accelerations, all on one or more axes according the sensors used. However, acquired values must be integrated to be used, increasing the uncertainty of the satellite attitude with time.

- Magnetic sensors: The magnetometer is an instrument that measures the magnetic fields to which are subjected the satellite on one or more axis according to the used sensor. The use of the map of the Earth's magnetic field associated to the knowledge of its orbit position, enable to obtain complete information about its attitude. However, these instruments are sensitive to electromagnetic interference generated by electronic systems and especially by magnetic torque actuators, so it is necessary of them outdistance at most from disruptive devices.
- The magnetometers in the SCAO can also be used to precisely determine the Earth's magnetic field to then calculate the command to send on magnetocouplers to get the desired attitude. The magnetic field intensity decreases rapidly with altitude; the use of magnetometers for attitude determination is reserved for the low earth orbit satellites.
- Other interesting sensors: Other sensors are available and may have an interest to be integrated into a satellite. There are, for example, the GPS receivers that can allow measuring the satellite position relative to the Earth (exclusively for satellites in Low Earth Orbit). But they are extremely expensive because of the high speed of the satellite.

2.2 Modification of the satellite attitude

It is possible to separate the many existing attitude control systems in two main categories: passive and active systems.

2.2.1 Passive attitude control

The passive attitude control presents the advantages of being robust, cheap, simple and to not consume power. It has nevertheless a limited pointing accuracy and does not allow to obtain all possible attitudes. Three passive stabilization types are primarily used.

<u>*Stabilization by gravity gradient:*</u>
The satellite's attitude stabilization is obtained from the torque created by the difference of gravity acting on parts of the craft far enough apart and rigidly connected.
<u>*Note:*</u> *This attitude control can only be used in the case of orbits of small eccentricity (such as the orbits used by the cubesats).*

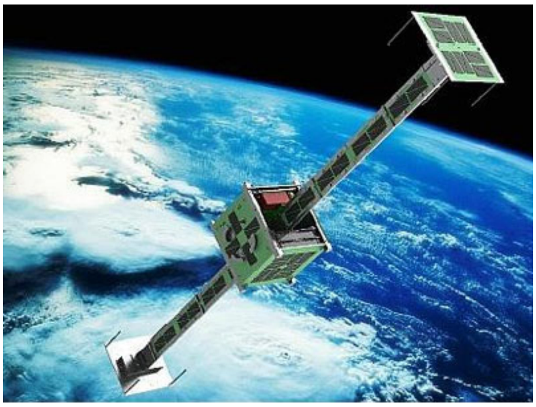

Figure 2. Unicubesat (University "La Sapienza di Roma")

<u>*Magnetic stabilization:*</u>
The satellite attitude stabilization is achieved by the magnetic torque generated by the interaction between magnets and the earth's magnetic field.
<u>*Note:*</u> *This attitude control method is dependent on the orientation of the geomagnetic field.*

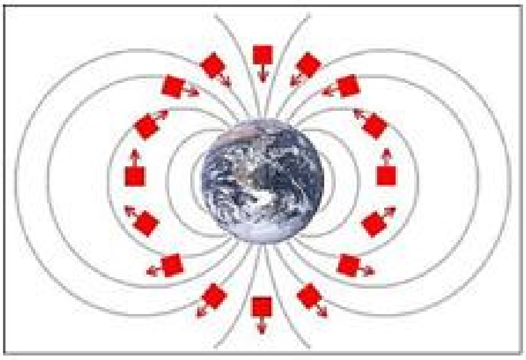

Figure 3. Magnetic stabilization

Stabilization by spin:
The attitude stabilization by "spin" uses the gyroscopic effect. The satellite is set in rotation around an axis to stabilize its attitude on this latter.
Note : This technique allow just the stabilization of a single axis.

2.2.2 Active attitude control

Active attitude control, with embedded electronic, actuators and sensors provides more precision and opportunities, but consumes energy and therefore has a limited life.
There are mainly three kinds used.

Stabilization by inertia wheels:
This type of attitude control requires the use of reaction wheels, which are a type of flywheel used for meticulous attitude change (eg: when a space telescope aims a star). The reaction wheels consist of an electric motor which puts a wheel in rotation of faster and faster until make turn the spacecraft in the opposite sense to the direction of the engine proportionally to the conservation of the angular momentum.
Note : This system allows to change the satellite attitude on its three axis to a fine way. However, the derivative in time to tend to rotate the engines more and more quickly and it is necessary to accompany them with coils for desaturate them.

Figure 4. Goliat (National University of Engineering - Romania)

Stabilization by thrusters:
The use of controlled thrusters is a relatively simple mean for stabilization. A thruster is a "all or nothing" actuator, giving a push or zero or constant at its maximum value.
However, in order to not disturb the satellite's trajectory, we must not create resultant and therefore generate only a pure torque. For that, the thrusters are generally associated by pairs in symmetrical positions on the satellite to give opposing thrusts.
Note: This stabilization method, rather bulky, is particularly suitable for space stations requiring

high torques.

Figure 5. Thruster of the V2 rocket

<u>*Stabilization by magnetic torque:*</u>
Coils are supplied in order to generate a magnetic field creating a couple with the earth's magnetic field. This has the effect to align the coil and therefore the satellite with the geomagnetic field.
<u>Note:</u> This technique allows to change the satellite's attitude on three axes (X, Y and Z) on condition that the rotation orbit of the satellite around the Earth allows it.

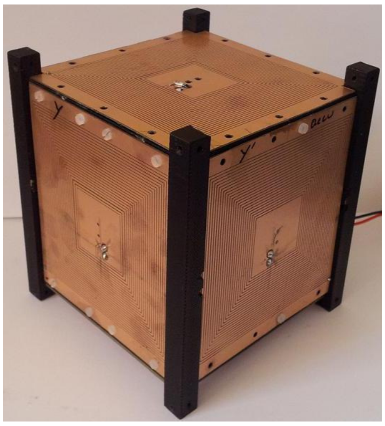

Figure 6. Mockup of the cubesat (INSSET)

3 IMPLEMENTED STRATEGY AND FIRST RESULTS

3.1 Constraints

Past few years, as part of some research projects, INSSET's students have successfully worked on the possibilities offered by electronic compasses (2D or 3D). Thus were developed a certain number of systems capable to interact with magnetic fields (generated by land or by magnets). That is why INSSET plans, all normally, the development of an Attitude Control System (ACS) for cubesat, based on the interaction of coils with the earth's magnetic field. The developed system will however respect numerous constraints (size, consumption ...).
It will, for example, be integrated in a 1U cubesat (10cm * 10cm * 10cm) without preventing the addition of a scientific experiment in this latter. It will also consume the least possible while having a good resolution for the change of the satellite attitude.

3.2 Acquisition system design

3.2.1 Used principle

To change the cubesat's attitude, the electrical current intensity browsing in coils, placed on each of its faces (cf Figure 6) is dynamically controlled.

Figure 7. Acquisition module

The electronic card controls the electrical current intensity as well as its direction making thus the cubesat as a magnet of magnetic moment *m*.
It is then possible to direct this vector *m* in any direction and change its module by simply controlling the I_x, I_y and I_z intensities circulating in the printed coils.

$$m = m_x + m_y + m_z \tag{1}$$

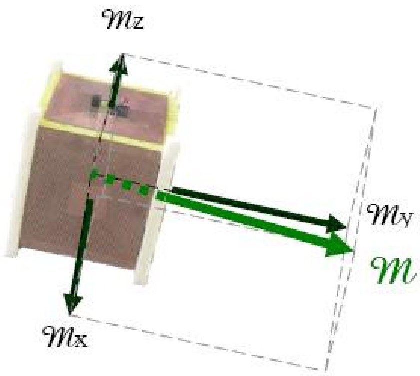

Figure 8. Magnetic moment generated by the coils

The interaction of these coils with the earth's magnetic field produces a force couple whose moment (M) is perpendicular to the magnetic induction vector of Earth (B_T) and the magnetic moment vector resulting from currents in the coils (*m*).

$$M = m \wedge B_T \tag{2}$$

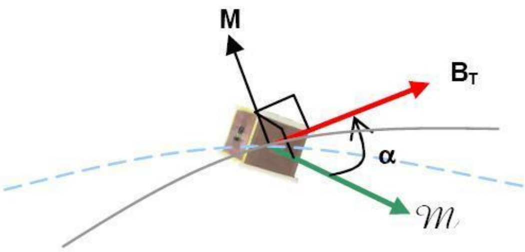

Figure 9. Magnetic torque between M and B_T

The moment tends to align *m* with B_T and thus to do rotate the cubesat in the direction of the angle α.

$$M = |m| * B_T * \sin(\alpha) \tag{3}$$

The moment of the torque is null when $\alpha = 0$ and maximum when $\alpha = \pi / 2$ rad, we therefore has an interest to control the currents circulating in the coils in order to fix m in a plane orthogonal to B_T to get the maximum efficiency in the attitude control. The torque moment M can be fixed only in a plane orthogonal to the vector B_T, it will thus be necessary to take into account this to apply the attitude control, this does not pose problems for polar orbits because B_T changes direction along the cubesat's trajectory, however, for equatorial orbits, the direction and sense of B_T do not change, M will therefore not act on the spin component parallel to the polar axis.

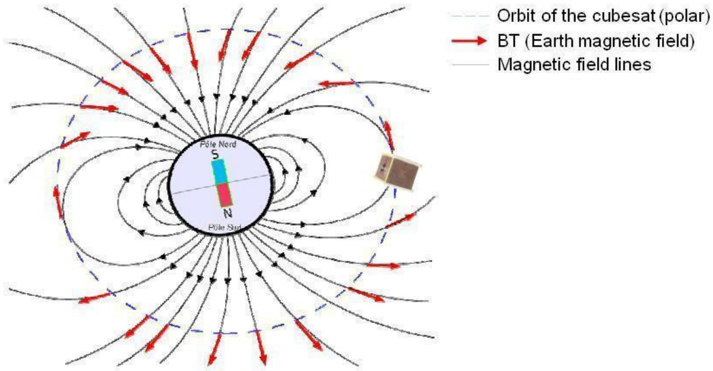

Figure 10. Earth magnetic field (B_T)

The magnetic field vector B_T depends on the cubesat's position on its orbit around the earth. The knowledge at any time of the cubesat's position on its orbit and of the Earth's magnetic field map are thus necessary for attitude control.
The control device must also be able to continuously measure the cubesat's attitude. For that, it is equipped with a magnetometer that measures the components of the vector B_T and a device for determining the direction of the sun in the reference frame of the cubesat. The knowledge of these two vectors and of the satellite's position on its trajectory then allows calculate the cubesat's attitude at a given time.
The coils supply is controlled by an embedded program. This program uses the orbit's characteristics, the indications of a real time clock and magnetoresistive sensors to determine the earth's magnetic field vector, and the voltages and currents of solar panels to get direction from the sun.
The speed vector is measured by a three-axis gyroscope (ADIS16405) allowing monitoring the cubesat's attitude and synchronizing the current pulses in the coils.

3.2.2 Bases of the used algorithm

The attitude control consists in modifying the rotation's speed vector of the cubesat on itself (spin) in direction and module.
We used a command by current pulses in the coils, synchronized on the cubesat's attitude, these pulses are calculated according to the modified desired speed and the measured parameters.
We neglect the frictions in residual atmosphere, the solar wind and other forces whose effects on the satellite's attitude are negligible compared to the forces of interaction between the coils and the earth's magnetic field.
We note [J] the inertial matrix of the cubesat, Ω_1 the initial rotational speed vector measured by the gyroscopes and Ω_2 the desired rotation vector.
The sensor (ADIS16405) gives the instantaneous rotational speeds relative to the cubesat inertial reference frame (Galilean) projecting in the reference frame of cubesat.
The inertial matrix values of the cubesat have been obtained experimentally with the torsion pendulum method. The coordinate axes are the principal axes, the inertia products are neglected.

$$J = \begin{bmatrix} 7.6e^{-4} & 0 & 0 \\ 0 & 8.38e^{-4} & 0 \\ 0 & 0 & 7.39e^{-4} \end{bmatrix} \qquad (4)$$

The angular momentum theorem can then be writed (galilean reference frame):

$$M = [J]\frac{d\Omega}{dt} \quad so \quad M.dt = [J].d\Omega \qquad (5)$$

By integrating and then discretizing, we obtain:

$$\sum_{i=1}^{n} Mi.\Delta ti = [J].(\Omega_2 - \Omega_1) \qquad (6)$$

$$\sum_{i=1}^{n} mi \wedge B_i.\Delta ti = [J].(\Omega_2 - \Omega_1) \qquad (7)$$

This last relationship is the basis to develop the attitude control algorithm. The pulse number *n* and their respective durations Δt depends on the desired speed variation, the inertia matrix J and the vectors *m* and B_T. The maximum magnetic moment *m* is limited by the maximum current available to power the coils. The direction of B_T is important because the torque moment M is in a plane perpendicular to B_T, it must thus wait for the right moment to apply the attitude control.

3.3 Cubesat modeling in microgravity

To collect experimental data to model the cubesat, a student group achieved a weightless flight, aboard the A300 Zero-G of Novespace [9].

During a parabolic flight, the aircraft of Novespace describes thirty-one trajectories in parabola's form, thus producing microgravity conditions for about 20 seconds per parabola. This microgravity effect is very interesting for the development of such a system because it allow to be in conditions close to those of a satellite in orbit and thus offers us working conditions impossible to reproduce in a laboratory. Data acquired during this flight will contribute thereafter to this system's development.

The experiment was composed by two mockups of cubesat and a laptop. One of this was used as reference and fixed to the plane's floor while the second evolved into free-floating. Each model contains a device for controlling the electric current intensity in three identical coils disposed on its three orthogonal axes (X, Y and Z) and a module allowing the acquisition of the Earth's magnetic field components (magnetometer), of the rotational speeds (gyroscope) and accelerations (accelerometer).

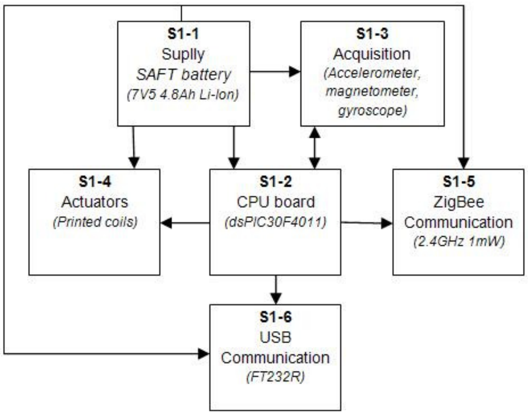

Figure 11. Block diagram of the electronic card

The results, - components Bx, By, Bz of the magnetic field, rotation speeds Ωx, Ωy, Ωz and accelerations Ax, Ay, Az -, were recorded onboard the mockup and sent in ZigBee to the computer.
These thirty sets of experiments, with video recordings, have allowed to make recordings under different scenarios, with manually induced initial speeds along several axes, and with different current levels in the coils.

Figure 12. Students front the A300 Zero-G (Novespace)

4 PROSPECTS

To acquire always more experimental data to model as best as possible a satellite in space, the INSSET institute seizes the opportunity of embark a payload into a satellite of type cubesat whose launch is planned for 2013.
This latter will be composed of an accelerometer, a gyroscope and a magnetic sensor (all three axes) and, optionally, of a GPS to know the position and behaviour of the satellite in space.
It should also embark one or two actuators (coils generating a magnetic field) and a small flash memory.

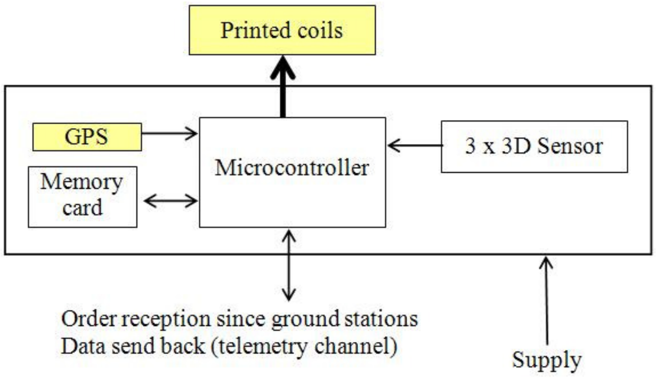

Figure 13. Functional diagram of the card to board

The experience, controlled by a series of basic commands via radio from ground, will have to role the transmission of instantly acquired data or previously recorded (as requested mission), to ground stations in order to model the behavior of the satellite in space during the creation of a magnetic torque between this latter and the Earth (sends of a step on the coils).
Finally, to improve the acquisition conditions, the embedded program will be automatically adjusted in function of the satellite's speed ($F_{AC} = F(v)$).

5 CONCLUSION

The cubesats projects enable collaboration with several schools such as the Lycée Condorcet (IRIST BTS) for the design of the diagnostic software for cubesat, the GMP IUT for the mechanical design of the satellite and the ESIEE (Engineering Production Systems) for its electrical part. A competition will also be organized between primary schools of the Saint-Quentin city to choose the name of the cubesat.
The upcoming study will serve to determine the feasibility of some interesting features which can be integrated into a satellite such as, for example, the antenna pointing to a station when passing near or even an early return to Earth at the end mission. It will also allow optimizing the system consumption and its bulk and learning many interesting facts about the behaviour of the satellite in space.
Finally, the attitude determination and control system will be integrated into a satellite developed in collaboration with the ELISA school in 2016.

6 ACKNOWLEDGEMENTS

The study of this system, as well as research contributory (microgravity flight, sends of the acquisition module in space) has been / will be achieved through the financial support provided by the Picardie region, the Saint-Quentin city (02), the CAPROM association, the FSDIE commission, the UPJV University of Amiens, the INSSET institute and the CNES.

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