GNC 2017 : 10th International ESA Conference on Guidance, Navigation & Control Systems
29 May - 2 June 2017, Salzburg, Austria
European Space Agency

Precision Attitude Determination And Control System of CubeSats by On-Orbit Determination of the Dynamic Magnetic Moment

Abdelmadjid Lassakeur, Prof Craig Underwood

Surrey Space Centre, BA Building, University Of Surrey, Guildford GU2 7XH, +441483 686025,
a.lassakeur@surrey.ac.uk , c.underwood@surrey.ac.uk

ABSTRACT

CubeSats are being increasingly specified for demanding Earth Observation and Astronomical applications where precise pointing, agility and stability are critical requirements. Such precision is difficult in the case of CubeSats as, firstly, their small moments of inertia mean that even small disturbance torques, such as those due to a residual magnetic moment, have a significant effect. Secondly, there are hardware limitations in terms of power, weight and size, which make the task more challenging.
Recently, a research programme has been undertaken at Surrey Space Centre, to study the source of the residual magnetic moment in CubeSats, and to characterise the effect of the resulting disturbance on the attitude of the spacecraft. It has been found that, although the disturbances may be minimised by good engineering practice, in terms of minimising the use of permeable materials, and minimising current-loop areas, these disturbances can still be an issue when a high degree of stability is required. The dynamic nature of the disturbances requires an active mitigation strategy. We therefore propose a new technique using a network of magnetometers to dynamically characterize and then compensate the residual magnetic moment in real time. This paper reports on our findings to date.

1 INTRODUCTION

CubeSats are built to standard dimensions, with a base unit volume (U) of 10x10x10 centimetres. They can be 1U, 2U, 3U, or 6U in size and less than 1.33 kg of mass per unit [1]. This concept was first proposed in November 1999 by Professor Robert Twiggs from Stanford University at the 2nd Space System Symposium. It has since been adopted widely by the universities and the space industry [2], 461 have been lunched up to 15 May 2016 [3]. CubeSats are a demonstration that very small size satellite technology developed; mostly, using commercial off-the-shelf (COTS) components; can perform practical space missions, often as university projects for space engineering students wanting to test out some new technology or technique [4]. This class of spacecraft is also being increasingly used for Earth observation and astronomical applications where precise pointing and high stability are critical requirements.

Given the power, volume and cost limitations of CubeSats, several challenges have to be addressed by the CubeSat community. One key challenge is the provision of a precise attitude determination and control system (ADCS), as the small size of the satellites means less volume, less mass and less power for sensors, actuators and algorithms processing [5]. Moreover, many CubeSats have been observed to suffer from unwanted magnetic dipole moments, which become the dominant source of attitude disturbances for such small moment of inertia platforms. To remedy this, the source of these disturbances should be reduced on the ground (e.g. by good design practices) and, ideally, any residual cancelled in-orbit, in order to achieve the required level of attitude control [4], [6].

The effect of magnetic disturbances has shown itself by the problem of high tumbling rates observed on several CubeSat missions. Post-flight analysis indicates this is due to un-modelled magnetic moments mainly caused by the current flowing in the spacecraft – both in the wiring harness and in the layout of the solar panels. Some CubeSats also carry permanent magnets – e.g. for electric motors – ironically often used in the ADCS systems for momentum wheels! However, by contrast, the other typical attitude disturbance sources for spacecraft (gravity gradient torque, aerodynamic torque, and solar radiation pressure torque) decreases significantly when the satellites become small [7]. The aim of this paper is to study these sources of the residual magnetic moment and the effect of the magnetic disturbance on the attitude of CubeSats, and a new technique is proposed, using a network of magnetometers to characterize and compensate the residual magnetic moment – in flight and in real time.

2 MAGNETIC DISTURBANCE CHALLENGES TO ATTITUDE DETERMINATION AND CONTROL SYSTEMS

For CubeSats operating in the vicinity of Earth, magnetic disturbances dominate over other environmental disturbances (gravity-gradient, aerodynamic and Solar radiation pressure torques) due to the Earth's magnetic field, which interacts with any residual magnetic field of the spacecraft that results in a magnetic dipole [8], [9], [10].

The magnetic torque (T) generated by the interaction of this dipole (m) with the Earth's magnetic field (B) is given by:

$$\vec{\boldsymbol{T}} = \vec{\boldsymbol{m}} \times \vec{\boldsymbol{B}} \tag{1}$$

2.1 Dynamic Magnetic Moment

The main sources of current loops in CubeSats that generate a dynamic magnetic moment in the spacecraft are from the harness of the spacecraft and from the layout of the solar panels. The current flowing in the solar panels (i.e. the cells and their associated wiring) generates a residual magnetic field due to the resulting current loops. Several methods are available in the literature, which can reduce these current loops [11], including placing tracks of opposite current flow next to one another, or laying them on top of one another in a multi-layer printed circuit board.

The battery generates a current loop that causes some dipole change when changing the charge or discharge rate of the batteries [12], but it usually doesn't have an important effect compared to other sources.

2.2 Static Magnetic Moment

The presence of permanent magnetic material in the spacecraft generates a permanent source of magnetic moment in the spacecraft, which does not vary over time. This source should be known and taken into account by the ADCS to cancel it using actuators when controlled attitude is required. Some CubeSats use such permanent magnets to provide their main form of attitude control. When coupled to a dissipative mechanism (such as a fluid loop or simply due to eddy current formation), the magnetic dipole becomes locked to the Earth's field – thus, making the magnetic dipole axis of the spacecraft track the Earth's magnetic field direction.

Many CubeSats use magnetorquer coils (or solenoids) to provide a controlled external torque for attitude control. This deliberate generation of a magnetic dipole is not a problem – it is only if the dipole is uncontrolled or unexpected that it becomes an issue. However, one consequence of actuating a magnetorquer, could be that any permeable material on-board the satellite becomes magnetised, thus leaving an unwanted residual dipole moment. It is for this reason, why magnetorquer solenoids make use of low-remanence ferromagnetic cores – such as Supra-50 alloy [13].

2.2.1 Hysteresis effects in soft ferromagnetic materials

Materials are magnetically divided into two classes, soft and hard magnetic materials, the first group have a large magnetic permeability and respond very sensitively to the presence of any external magnetic field, this means that they can easily be magnetised and produce a very strong magnetic field. On the other hand, hard magnetic materials need a very large external field before they become contaminated. Therefore, the use of hard ferromagnetic or non-ferromagnetic materials such as aluminium are suitable for spacecraft magnetic cleanliness, whereas soft magnetic materials such as mild steel are not [14].

3 CHARACTERIZATION OF THE SATELLITE RESIDUAL DIPOLE

To compensate the magnetic disturbance precisely, the residual magnetic dipole has to be measured or estimated accurately. Different methods exist in the literature to estimate the residual dipole (expressed in units of Amp-m^2) of a spacecraft in orbit by using magnetic field models for the Earth and knowledge of the inertial properties of the spacecraft (captured in the inertia tensor – i.e. the matrix comprising the 3 moments of inertia and the 6 products of inertia) [15]. However, difficulties arise when it comes to effectively *measure* (rather than estimate) the magnetic dipole moment.

3.1 Residual Dipole Characterization

On the ground, determination of the spacecraft's magnetic moment dipole magnitude and direction require an accurate knowledge of the strength and direction of the surrounding magnetic field of the spacecraft. Many techniques were successfully developed by NASA in early 1960s and are described in detail in [16]. However, these methods have some limitations – for example, one of the techniques used – the resonance technique – is designed only to measure small dipole moments of large spacecraft [17].

Three other methods have been used by Intespace and Centre National d'Etudes Spatiales (CNES) in Toulouse, France:

- The first is the “6 faces” method that involves measuring the magnetic field at the centre of the 6 faces of the (cuboid-shaped) spacecraft and the equipment then calculates the magnetic moment considering a centred dipole approximation.
- The second, is the determination of the Fourier coefficients of 3 circular magnetic field measurements on the 3 orthogonal planes (XY, YZ and ZX).
- The third technique was developed in 2012, and consists of using spherical measurements and spherical harmonics modelling [18].

By assuming the spacecraft field to be a dipole magnetic field, the far field is easily resolved using the methods described in [19]. This is also used for the geomagnetic field determination, whereas the complexity of the determination of magnetic dipole arises when it comes to the near magnetic field scaling, two main theoretical methods have been used in the literature:

- The first is defined in [20], this method uses spherical coordinates to determine the magnetic dipole moment
- The second method is described in [14] and uses Cartesian coordinates, where it is possible to take many measurements of the magnetic field close to the spacecraft then compute the dipole. The magnetic field as a function of the generated dipole in free space, is given by Eq. 2:

$$\vec{\boldsymbol{B}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = \frac{\boldsymbol{\mu_0}}{\boldsymbol{4\pi}}\left[\frac{3\hat{\boldsymbol{r}}(\hat{\boldsymbol{r}}.\vec{\boldsymbol{m}})-\vec{\boldsymbol{m}}}{|\vec{\boldsymbol{r}}|^3}\right] \tag{2}$$

Where

$\vec{B}(x,y,z)$ = the magnetic field at the location (x,y,z)

μ_0 = the permeability of the free space

$\vec{m}$ = the magnetic dipole moment

$\vec{r}$ = the vector from the dipole to (x,y,z)

$\hat{r}$= the a unit vector in the direction of $\vec{r}$

After some manipulations, equations Eq. 3 to Eq. 5 may be derived, which describe each component of the magnetic field B_x, B_y and B_z as a function of its location (x,y,z) and the magnetic dipole location (a,b,c). The dipole has an orientation which is described by a unit vector with components (m, n, p) and a total dipole magnitude of S [21].

$$B_x = \frac{\mu_0.S}{4\pi}\left[\frac{3[m(x-a)+n(y-b)+p(z-c)].(x-a)}{R^5} - \frac{m}{R^3}\right] \tag{3}$$

$$B_y = \frac{\mu_0 . S}{4\pi}\left[\frac{3[m(x-a)+n(y-b)+p(z-c)].(y-b)}{R^5} - \frac{n}{R^3}\right] \qquad (4)$$

$$B_z = \frac{\mu_0 . S}{4\pi}\left[\frac{3[m(x-a)+n(y-b)+p(z-c)].(z-c)}{R^5} - \frac{p}{R^3}\right] \qquad (5)$$

R is the distance from the dipole to (x, y, z) and is given by

$$R = \sqrt{(x-a)^2 + (y-b)^2 + (z-c)^2} \qquad (6)$$

For both methods, given magnetic field measurements at known locations, six unknowns have to be determined.

4 METHODOLOGY AND EXPERIMENTS

4.1 Magnetic Cleanliness

No spacecraft can be integrated without incurring a residual magnetic field generated by itself from the wiring and its electronic and electromechanical components. This can be an important source of ADCS disturbance. The critical instruments and sensors of the mission (e.g. magnetometers) need to be protected from these spurious magnetic fields if the external field needs to be measured accurately.

To minimize the magnetic sources on-board the satellite, a so-called magnetic cleanliness program can be run by employing the following plan to ensure that the spacecraft magnetic field stays sufficiently low [22]:

- Avoid using ferromagnetic materials wherever possible.
- Reduce the current loops in cabling and solar panels.
- Identify the magnetic sources as early as possible and minimize them.
- Characterize the identified magnetic sources by measuring and modelling their magnetic behaviour.
- Calculate and measure the influence of all magnetic sources on the instruments.
- Use magnetic field compensation methods to minimise the residual magnetic field at the location of the instrumentation [22].

4.2 Magnetic Sensor Calibration

For precise and reliable magnetometer readings, magnetometer calibration is a critical part of magnetic-based attitude deamination systems [21]. The calibration should include: sensitivity calibration, sensor zero offset and misalignment between magnetic and mechanical axis. If a boom is used, the misalignment angles is between sensor axes at the end of the boom and the body coordinate system [23].

4.2.1 On-board Calibration of the Magnetometer

Magnetometer measurements are disturbed by the magnetic fields created internally, this limits their utility on satellites. To mitigate this disturbance, a boom should be used to provide physical separation between the magnetometer and the satellite [24].

A dual magnetometer method has been applied in many spacecraft to detect spacecraft stray fields, such as on Giotto, Cassini, Ørsted, MAGSAT and Solar Orbiter, the latter is under development and will be launched in 2018. This technique is basically used for the purpose of decontaminating the magnetometer reading from the spacecraft field [23], [25] .

Other methods of in-flight correction of magnetometer zero offsets has been discussed in [14].

4.3 Residual Dipole Moment Determination Techniques

Having applied the magnetic cleanliness programme to the satellite and alleviated the residual magnetic moment during the definition of the mission and the integration of the spacecraft, the ultimate goals of this research are to develop a reliable method to characterize the magnetic dipole of the spacecraft both on the ground and in operation in orbit. For the ground tests, a Helmholtz coil arrangement is used to null out the Earth’s magnetic field, and then a series of magnetometers are arranged around the spacecraft to measure the field just outside the spacecraft body. We then apply the method described in [14] to determine the dipole moment in different operational configurations. The new idea is to use a set 8 miniature 3-axis magnetometers distributed around the spacecraft to determine the residual magnetic dipole on-board the satellite in orbit, and to do so, such that the information is available to the ADCS control loop so that this (dynamic) dipole can be compensated in real time. The advantage of this technique is that the control of the spacecraft can be improved without the need of changing the existing ADCS hardware – simply adding in 8 more magnetometers (assuming one is already present). Fig.1 shows the proposed layout of the magnetometers on a typical 3U CubeSat.

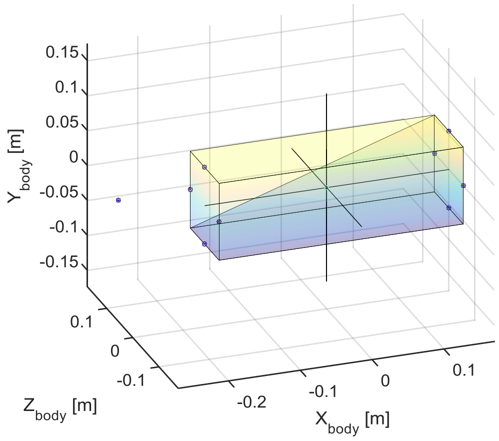


Figure 1. Magnetometers positions in 3U CubeSat

- The outer (boom-mounted) magnetometer is used as a reference reading of the external magnetic field.
- The surface mounted magnetometers on the spacecraft will serve as an input to the algorithm which will determine the strength and the centre of the magnetic dipole of the spacecraft.
- Finally, the magnetorquers and the momentum wheel (and thrusters if they exist) will serve to compensate the measured residual magnetic moment in-orbit.

Fig.2 shows a system diagram for the concept.

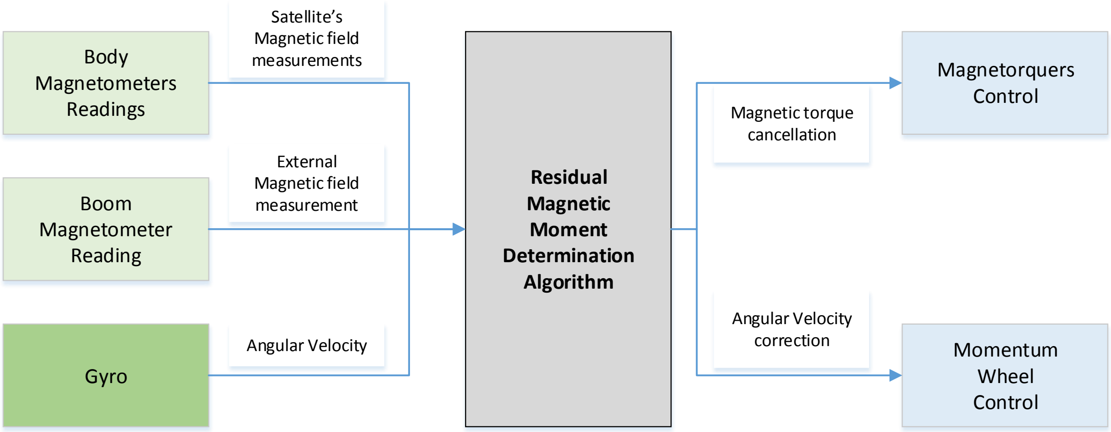


Figure 2. Residual magnetic moment determination and cancellation strategy

4.3.1 Magnetometers selection

A survey has been conducted to select the most suitable magnetometer for this research. Out of many magnetometers in the market, the Honeywell HMC1053 three-axis magnetometer was selected (Fig. 3). These are magnetoresistive sensors designed for low level magnetic field sensing. They have low power consumption, can be used over a wide temperature range, and they are already used on-board many CubeSats. The main problem of this type of magnetometer is that its output drifts with temperature, and therefore it needs careful calibration. Table 1 summarises its properties.

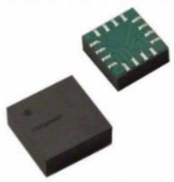


Figure 3. Honeywell HMC1053 three-axis magnetometer

Table 1: Honeywell HMC1053 three-axis main characteristics

Characteristics	Min	Type	Max	Units
Supply	1.8	3.0	20	Volts
Operating temperature	-40	-	125	^{0}C
Field Range	-6	-	+6	gauss
Resolution	-	120	-	µgauss
Bandwidth	-	5	-	MHz

4.4 Magnetic field measurements of AlSat-1N CubeSat

4.4.1 Helmholtz Coil Test Facility

The ground testing technique described above was applied to the AlSat-1N CubeSat. A set of 3-Axis Helmholtz Coils was constructed and used to null out the Earth's magnetic field at the satellite (Fig. 4).

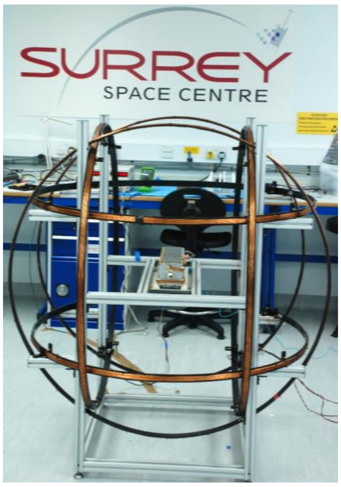


Figure 4. The 3-Axis Helmholtz Coil test facility with AlSat-1N inside

4.4.1.1 Static Magnetic Field Measurements

The static magnetic field of the spacecraft was measured when the spacecraft was turned off inside the Helmholtz Coil. The measurements of this test were used to determine the magnetic dipole of the spacecraft and the result is illustrated in Fig. 5(a). Other configurations were tested as follows:

As shown in Fig. 5 (b), the spacecraft was turned on, including the battery and ADCS, and none of the payloads were turned on.

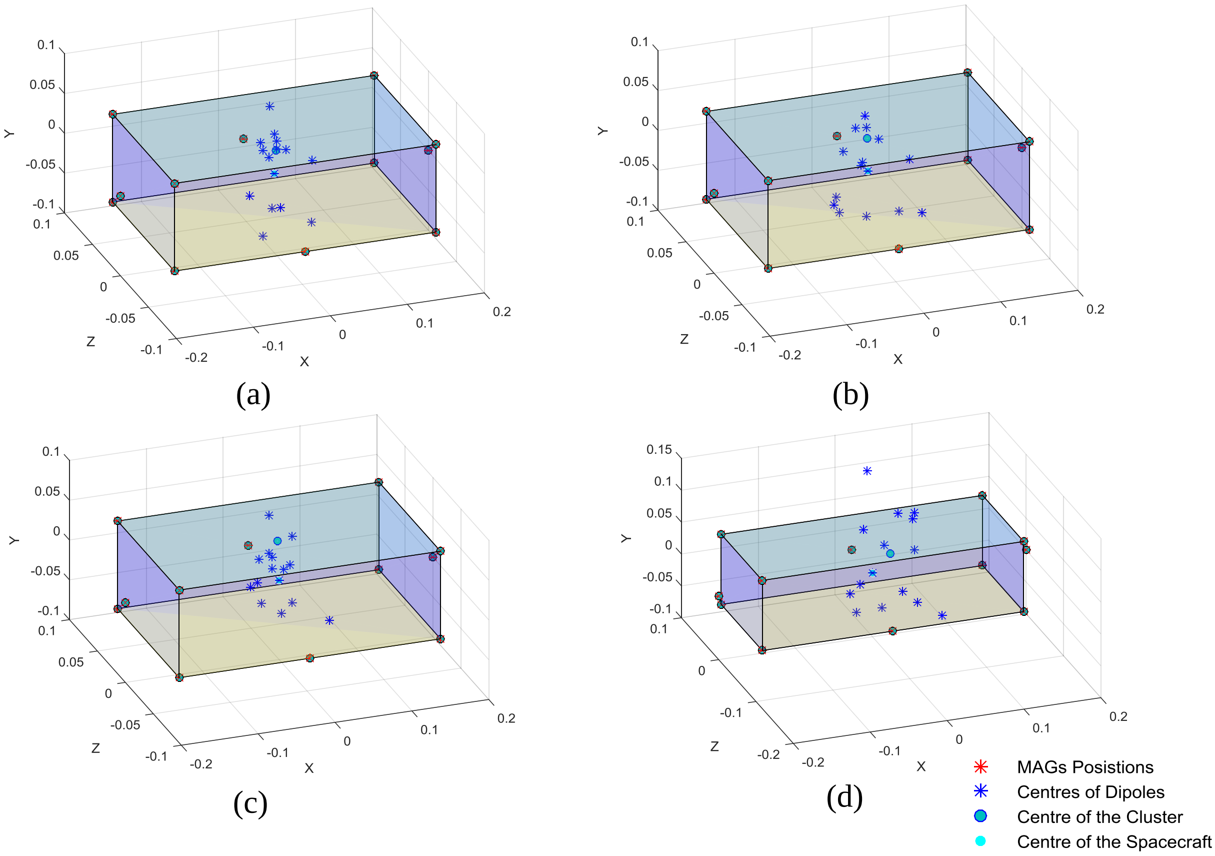
In Fig. 5 (c), the spacecraft was turned on, including the battery and ADCS, none of the payloads were turned on, and solar panels were lit from the +Z facet using a 500W halogen lamp from 30cm distance.

In Fig. 5 (d), a similar test was carried out, but the solar panels were lit from the opposite (–Z) facet.

The results shown in Fig. 5 (a-d) give an idea of the position of the dipole computed by means of many measurements. As can be seen, the layout of the calculated centres of the dipole is scattered around the centre of the spacecraft and is not tending to a single location – as would be expected. This, we believe, is due to the inaccuracy and mono-axis of the magnetometer used in this first test, especially given that the readings were not taken simultaneously throughout the test.

What is encouraging is that the clusters do tend to centre around the middle of the 3U structure, which is where we believe the true dipoles lie.

In future testing with the 9 three-axis magnetometers, we expect to achieve more accurate values of the magnitude and the centre of the dipole. Also, we shall use more sophisticated statistical techniques in the data reduction such as least-square fitting and random sample consensus (RANSAC). We shall also be able to synchronise the measurements, so that the field can be properly estimated at a particular instant of time. The circuit developed to read the magnetometers is based on the Raspberry Pi compute module 3 and ADS1115 which is an I2C analog-to-digital converter (ADC). The circuit is capable of reading all 8 magnetometers (24 readings) in less than 10ms.



(a)

(b)

(c)

(d)

Figure 5. Centre of dipoles from a couple of measurements

5 CONCLUSION

Attitude determination and control systems of CubeSats have always suffered from their limitations, in terms of size, weight and power. CubeSats face an unwanted magnetic moment in orbit, which, because of the small moment of inertia of the satellite, is a dominant source of attitude disturbances.

As discussed in this paper, all spacecraft have an associated magnetic field that depends on its material properties and the presence of current loops. Solar arrays should be designed to minimize generated magnetic disturbances, including the avoidance of using magnetic materials and a vigorous application of magnetic field cancellation techniques. Shunning of ferromagnetic materials is possible by careful material selection. Surveys of COTS solar arrays for CubeSats indicate that they are often not designed with magnetic cleanliness in mind. Therefore, magnetic cleanliness awareness should be spread across the CubeSat community so that developers take into account this issue.

This research project proposes a new method to characterize the residual magnetic dipole moment of the spacecraft and cancel this disturbance, in-orbit, by implementing a network of 8 surface-mounted 3-axis magnetometers on the spacecraft, with an additional one mounted on a deployable boom. These will be used to determine the strength and the centre of the magnetic dipole of the spacecraft dynamically, in-flight and in real-time. The information will be used by the ADCS control loops and actuators to compensate the measured residual magnetic moment. This technique will contribute to achieving more precise pointing, agility and stability of CubeSats and can be generalized for bigger spacecraft.

A start has been made by measuring the dipole centre of the AlSat-1N 3U CubeSat before flight using several magnetometer readings. A hardware prototype of our 9 3-axis magnetometer system is being developed and tested with the engineering model of Alsat-1N at Surrey Space Centre to demonstrate the efficiency of this technique proposed in this paper.

Acknowledgements: The authors acknowledge the financial and logistical support for this research provided by The Algerian Space Agency (ASAL) and the UK Space Agency (UKSA), to whom we are grateful. We should also like to thank the ASAL and SSC staff involved in the integration of the AlSat-1N spacecraft, and in its on-going operation.

REFERENCES

[1] Munakata R., *CubeSat Design Specification, The CubeSat Program,* Cal Poly SLO, vol. 12, 2008.
[2] Abbas N. N., *et al. An Architecture Analysis of ADCS for CubeSat: A Recipe for ADCS Design of ICUBE*, pp. 5397-5404, 2012.
[3] *Nanosatellite Database*, 23/06/2016; http://www.nanosats.eu/.
[4] Inamori T., Sako N., and Nakasuka S., *Compensation of time-variable magnetic moments for a precise attitude control in nano- and micro-satellite missions, Advances in Space Research*, vol. 48, no. 3, pp. 432-440, 2011.
[5] Quadrino M. K. *et al.*, *Testing the attitude determination and control of a CubeSat with hardware-in-the-loop*, 2014.
[6] Steyn W., and Hashida Y., *In-orbit attitude performance of the 3-axis stabilised SNAP-1 nanosatellite*, 15th Annual AIAA/USU Conference on Small Satellites, Utah State

University, Logan USA, 2001.
[7] Shin-ichiro S., Yosuke F., and Hirobumi S., *Design and On-Orbit Evaluation of Magnetic Attitude Control System for the REIMEI Microsatellite*. pp. 584-589, 2008.
[8] De Ruiter A. H., Damaren C., and Forbes J. R., *Spacecraft dynamics and control an introduction*, 2012.
[9] Inamori T., Nakasuka S., and Sako N., *In-orbit magnetic disturbance estimation and compensation using UKF in nano-satellite mission, 2009*.
[10] Inamori T., and Nakasuka S., *In-orbit magnetic disturbance compensation using feed forward control in Nano-JASMINE mission*, Small Satellites Conference, Utha, USA, 2008.
[11] Theodore S., and Scott D., *Techniques for Magnetic Cleanliness on Spacecraft Solar Arrays*, 2nd International Energy Conversion Engineering Conference, (IECEC): American Institute of Aeronautics and Astronautics, 2004.
[12] DeKock B., et al. *Design and Integration of an All-Magnetic Attitude Control System for Fastsat-Hsv01's Multiple Pointing Objectives*, Guidance and Control, 2011.
[13] Miller D., *MXL Tech Memo, Technical report*, Michigan Exploration Laboratory, 2013.
[14] Pudney M., *Advances in spacecraft magnetic cleanliness verifcation and magnetometer zero offset determination in anticipation of the solar orbiter mission*, Imperial College London, 2014.
[15] Mysore Srinivasa K., *Spacecraft Attitude Control Using Magnetic Actuators*, 2015.
[16] Schalkowsky S., et al. *Spacecraft magnetic torques*, Springfield, 1969.
[17] Tossman B. E., *Resonance technique for measurement of satellite magnetic dipole moment*, NASA, United States, 1965.
[18] Dumond O., Berg R., and x00E, *Determination of the magnetic moment with spherical measurements and spherical harmonics modelling*. pp. 1-5, 2012.
[19] Hastings D., and Garrett H., *Spacecraft-environment interactions*: Cambridge university press, 2004.
[20] Eichhorn W. L., *Magnetic dipole moment determination by near-field analysis*, Goddard Space Flight, 1972.
[21] John S., James C., and Hasan B., *Magnetic Sensor Calibration and Residual Dipole Characterization for Application to Nanosatellites*, AIAA/AAS Astrodynamics Specialist Conference, Guidance, Navigation, and Control, American Institute of Aeronautics and Astronautics, 2010.
[22] Ley W., Wittmann K., and Hallmann W., *Handbook of space technology*, John Wiley & Sons, 2009.
[23] Musmann G., *Problems with magnetic field measurements on spacecrafts*, Deutsche Hydrografische Zeitschrift, vol. 41, no. 3-6, pp. 265-276, 1988.
[24] Springmann J. C., *Satellite Attitude Determination with Low-Cost Sensors*, University of Michigan, 2013.
[25] Carr C., *et al.*, *The Double Star magnetic field investigation: Instrument design, performance and highlights of the first year's observations*. pp. 2713-2732, 2005.