Methods for a detumbling algorithm for 2U CubeSat

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***Abstract*—Following the launch of a satellite to space the first challenge a satellite encounters is tumbling, tumbling occurs when the satellite is separated from the launcher and finds itself rotating in an uncontrollable manner. Acquiring attitude of the satellite is crucial in order to attain the desired payload attitude. This initial attitude acquisition procedure, commonly known as detumbling, is the first task of the Attitude Determination and Control Systems (ADCS) module.**

Although three-axis control is typically attainable using thrusters, due to the mass limitations on a 2U CubeSat, the application of magnetic torquers for detumbling seems to be the most prominent method for attitude acquisition of the satellite. This paper explores the distinct methods for magnetic detumbling including the traditional b-dot control law with it's variations, while comparing their performance with an alternative magnetic detumbling method, passive detumbling and angular velocity feedback.

***Index Terms*—detumbling algorithm, controller, b-dot controller, PID controller, attitude determination**

I. Introduction

A CubeSat is a class of research spacecraft called Nanosatellites [1]. CubeSats are built to standard dimensions of 10cm x 10cm x 10cm, this units depicted by the letter "U" have a number before expressing the number of "cubes" of unit "U" stacked amongst themselves, CubeSats typically weigh less than 1.33 kg per "U" [2]. CubeSats are usually deployed from a Poly-Picosatellite Orbital Deployer(P-POD). After the CubeSats ejection from the P-POD, just as any satellite during the launch stage, the CubeSat is influenced by an external force from the separation of the satellite from its vessel. This force leads to an inevitable motion known as tumbling, in order to acquire the satellites attitude it is crucial to de-tumble in order to later direct the satellite to it's determined attitude. In contrast to bigger commercial satellites, 2U CubeSats lack the volume and space conventional satellites have, therefore the use of thrusters for attitude acquisition is not optimal due to the CubeSats constraints of the size, weight and power. Thus, the use of magnetic actuators is commonly used across the field, although the use of magnetic actuation leads to a less accurate and longer attitude acquisition time; the portability and low requirements of magnetic actuation becomes a perfect fit for the needs of a CubeSat.

Magnetic coils have been used as means of spacecraft orientation for a long time, such magnetic coils also called magnetorquers serve as a simple yet efficient torque generation mechanism for attitude control. Their operation is based on the interaction between the Earths magnetic field and the magnetic field generated by the coils, generating a controllable torque acting on the CubeSat [3].

Due to the introduction of new technologies such as thrusters, solar arrays and their variations; Magnetic actuation as a method of attitude control and momentum management had lost it's popularity until the introduction and popularization of CubeSats, thus the research and available information on magnetic detumbling lacks. Only approximate solutions dealing with such time-varying actuators are available, while periodic control has been proved successful in various applications. Therefore the purpose of this paper is explore the distinct methods already existent and to depict the alternative methods and variations that are yet to be explored and compared.

II. System Definitions

A. Defining the Coordinate System Frames

Due to the different possible reference points in space it is important to define the different coordinate frames used:

1) Earth Centered Inertial (ECI): Origin is located in the Earth's center, with the z-axis pointing in the direction of the north pole, x and y axis pointing in the equators direction orthogonal.

2) Earth Centered Earth Fixed (ECEF): Similarly to the ECI coordinate frame with the difference that the X-axis points exactly at the intersection of the equator and the Greenwich Meridian and corollary the Y-axis following the right hand rule direction is pointing +90 orthogonally to X-axis.

3) Simulations Coordinate Frame: Origin is located at the satellite's center of mass/gravity, the Z-axis points to the center of the Earth, X-axis points in the direction of the Velocity and consequently the Y-axis in the right hand frame.

4) Body: Same coordinate system as the simulation's CF with the exception that this frame rotates about the simulations frame denoted as ω_{b0}^{b}

B. Attitude

The way two coordinates frames are rotated is called Attitude in the industry of aerospace. The Attitude is described by the rotation matrix R_b^a, where a and b are two coordinates

used for an easier illustration of the definition. Both a and b have the coordinate vectors$x^a + x^b$ where:

$$x^a = R_b^a x^b and x^b = R_a^b x^a = (R_b^a)^T x^a \tag{1}$$

C. Angular Velocity

Angular Velocity ω_{ab}^a or ω_{ab}^b expressed as the rate of change of rotation Matrix, thus the derivative of the rotation matrix is:

$$\cdot R_b^a x^b = S(\omega_{ab}^a) R_b^a = R_b^a S(\omega_{ab}^a) \tag{2}$$

Where S( ) is cross product operator. Since the Gyroscope is fixed to Body the angular velocity of the inertia frame with respect to the body from ω_{ab}^a.

Detumbling consist of reducing ω_{ab}^a or $-\omega_{ab}^b$ thus, constant attitude of the body frame to the orbit frame.

D. Equations of Momentum/Torque

Due to the sizing limitations on the u-sat, the industry standard actuators which come to be thrusters are uncommon in CubeSats due to the lack of space for them and their fuel tank, therefore it has now become an industry standard to use magnetic actuation. The use of electromagnets generates magnetic dipoles of which if the flux amongst them and the earth's magnetic field is strong enough generates torque by interaction. This way shows to be relatively cheap and reliable as there are no moving parts, thus less space for error. Nevertheless, this method proves to be unable to create non-perpendicular, parallel, torque to the earth's magnetic field. Thus the standard set up consists of three electromagnetic coils aligned to the three principles satellites frame axis, enabling the creation of torque in all directions orthogonal to the earth's magnetic field.

Therefore, the torque can be mathematically formulated as:

$$\tau = S(m)B \tag{3}$$

Where m represents the magnetic dipole moment, B represents the flux density vector of the Earths magnetic field.

$$M = \frac{NA}{R} V \tag{4}$$

Where V represents the voltage applied to V_x, V_y, V_z

$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = S(\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}) * \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \begin{vmatrix} 0 & -B_z & B_y \\ B_z & 0 & -B_x \\ -B_y & B_x & 0 \end{vmatrix} * \begin{vmatrix} \frac{N_x A_x}{R-x} & 0 & 0 \\ 0 & \frac{N_x A_x}{R-y} & 0 \\ 0 & 0 & \frac{N_x A_x}{R-z} \end{vmatrix} * \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \tag{6}$$

We can further simplify the equation above to its equivalent:

$$\tau = s(-B) * K * V \tag{7}$$

where k represents the coil's constant.

III. Detumbling Control Laws

The concept behind detumbling relies on damping the angular velocity of the CubeSat to zero. Using the well known Euler's equations we can describe the evolution of the angular velocity of a body reference frame centered at the spacecrafts center of mass aligned with the principal axes of inertia, given by:

$$\dot{\omega} = I^{-1}(\tau - \omega \times I\omega) \tag{8}$$

where ω represents the angular velocity of the reference frame with respect to the inertial frame, τ represents the sum of the external torques and I represents the spacecrafts inertia. It is important to depict that all quantities expressed in (1) are represented in the body frame assuming the spacecraft to be a rigid body.

For the purpose of this study no external disturbances are considered, therefore, τ represents the control torque generated by the magnetic actuators:

$$\tau = m \times b \tag{9}$$

where m is the determined magnetic dipole moment and b is the local earths magnetic field vector. It is possible to use suitable approximations for the Earths local magnetic field based on altitude found in the International Geomagnetic Reference Field(IGRF) article [4] , yet the author Erwan Thebault of the previous IGRF article has provided a location specific model that can be used for an accurate approximation of the local Earths magnetic field at a specific location in orbit found here [5]

Looking at equation (9) it is important to understand that no torque is generated when $m \parallel b$ and that the arm is maximized when $m \perp b$. Moreover, a beneficial consideration for the implementation of a detumbling controller is that the control torque has to be proportional to $-\omega$, in order to decrease the kinetic energy of the spacecraft.

IV. Controller's Comparison

A. B-dot Controllers

The B-Dot controller, is a controller widely used across the aerospace industry which just like any other detumbling method relies on generating an opposing torque to the satellites "natural torque". Yet, the difference upon the b-dot controller in contrast to the other methods depicted in this paper is that the b-dot is dependant upon the earths magnetic field. Meaning, that the b-dot controller requires to know either an approximation or the exact current earths magnetic field at the current location.

1) Proportional B-dot: The B-dot control law uses as an advantage the fact that the derivative of the magnetic vector $\dot{b}$ is both proportional to ω and perpendicular to b in order to express the magnetic dipole as:

$$m = -k\dot{b} \tag{10}$$

where k is the positive gain.

2) Bang-Bang B-dot: A way to accelerate the b-dot controller decaying the spin of the CubeSat, is by employing a bang-bang solution of the following form:

$$m = -m_{max} sgn(\dot{b}) \tag{11}$$

where m_{max} is the maximum torquer dipole.Alternatively to the proportional B-Dot controller, instead of using the proportional control to calculate the dipole command, the maximum torquer strength is always used. The specific math depicting why the bang-bang bdot controller is faster than the proportional b-dot controller can be found here [6].

3) Enhanced B-dot Controller: A slightly different approach for a faster B-dot Controller proved by Antoine 18 is the addition of more coils in the CubeSat, although there is a space constraints in CubeSats if the requirements for the CubeSat payload are a fast detumbling process and there is enough space; The addition of three extra coils, six coils total, would allow a faster attitude acquisition setting 2 coils per axis completely parallel. This B-Dot would be enhanced on the fact that the coils would have to synchronously operate in opposite maximums. Meaning that when an axis needs to generate a torque, one coil will operate in positive maximum while the opposite coil will operate in negative maximum, hence generating a much stronger torque which will accelerate the data acquisition process time.

Since $\dot{b}$ can be calculated from the on-board sensors and simple computation, it is not required to know the information of the angular velocity of the CubeSat by eqs. (10) and (11). The B-dot controller usually operates in two different ways, with an Average approximation of the Earths magnetic field or an approximation of the Earth's varying magnetic field. Due to the Earths magnetic field periodic effect, many active Bdot controllers use the Average earths magnetic field. Depicted in fig. (1) are the block diagrams depicting the stages each bdot modes of operation use[7]. .

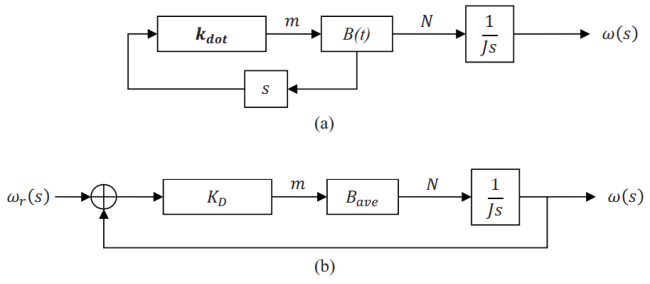


Fig. 1: Block diagrams for b-dot controller for (a) varying magnetic field (b) average magnetic field

B. Earths Magnetic Field Independent Controllers

1) Angular Velocity Feedback: When attitude information is available from the CubeSats on board sensors the following control law depicted by Avanzini and Guilietti [8] can be used for detumbling:

$$m = -\frac{k_\omega}{||b||^2}(b \times \omega) \tag{12}$$

where k_ω represents the positive gain and $(b \times \omega) \approx b \propto \omega$. Avanzini and Guilietti depict that the application of the Angular Velocity feedback control law in the presence of a time-varying magnetic field, the kinetic energy will decrease hence approaching zero assuring a global asymptotic stability.

2) Passive Detumbling: A simple and robust way of detumbling the satellite in LEO is the use of passive magnetic stabilization [9]. This is achieved with the use of permanent magnets being aligned along the satellite's axis. Therefore, the interaction of the permanent magnets with the Earths magnetic field will align the satellite. Antoine suggest that an effective way of accelerating the alignment is by building a structure out of out of permeable material which will act as a damping force needed to accelerate the alignment. This will reduce the rotational movements due to hysteresis.

V. Simulation Results

In order to compare the previously stated detumbling methods, a simulation performing a detumbling maneuver has been done in order to gain quantifiable visual data to compare each ,method of detumbling.The Cubesat Simulated being a 2U Low Earth Orbit(LEO) satellite equipped with first three and then 6 magnetic coils. The following were are the most relevant parameters:

- Orbital Radius: 7000km
- Inclination: 65 deg
- Inertia Matrix: $I = diag([0.33, 0.37, 0.35])Kg \cdot m^2$
- Max Magnetic Dipole Moment: $m_{max} = 2A \cdot m^2$ per Axis.
- Initial Angular Velocity: $\omega_0 = [0.604, 0.706, 0.384]^T$
- Control Sampling Rate: $10Hz$.

Concerning the value for the control gain k_ω, it was estimated by Hablani, in [10], as:

$$k_\omega = 2n(1 + \sin\epsilon)I_{min} \tag{13}$$

where n represents the mean average motion, ϵ represents the inclination of the orbit plane with respect to the equator and I_{min} represents the minimum moment of inertia of the spacecraft.
Concerning the proportional control law, the following static and time varying gains are as follows respectively:

$$k^* = \frac{k_\omega}{||b^*||^2} \tag{14}$$

$$k = \frac{k_\omega}{||b||^2} \tag{15}$$

where $||b^*||^2$ represents the average squared norm of the magnetic field over a revolution.

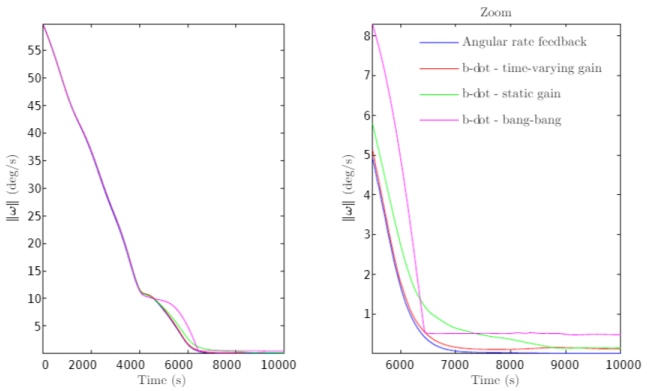


Fig. 2: Comparison of the detumbling control Laws: Bdots and Angular rate feedback

As depicted in fig.(2), provided by [11], Mirko's test result using the same parameters for the simulation as the papers visually demonstrate how initially the deceleration is closely identical due to the magnetic coils saturation. Yet, once zoomed in the Angular Rate feedback controller converges to zero the fastest, while the bdot time varying gain approximates it. Nonetheless, the bang bang b-dot controller depicts its on off nature by showing the steepest slope, hence minimum convergence time, with the cost of a higher final error. Mirko discusses in greater depth the outcomes of the simulation here[11], where he covers the detumbling control laws ideal performance and specific operations.

Moreover, due to the span of this paper, the simulation of the enhanced b-dot controller and passive controller stay beyond the scope of the paper, however in a theoretical analysis it is sufficient to say that the performance of the passive controller in comparison with the other controllers would be much slower after any perturbance due to the nature of the weaker always on torques generated by the interaction of the magnetic field with the permanent magnets. Nonetheless, the hypothesized error of such controller would be minimal once again due to the constant interaction of the magnets with the Earths magnetic field.

Furthermore, the hypothesis performance of the enhanced b-dot controller would in theory have a faster convergence rate to zero state but would jeopardize it's final error by increasing it. Due to the fact that the increase of equipment yields to the increase in instrumental error.

VI. Conclusion

Based on the previously stated arguments and the results obtained from Mirko's simulation, we can conclude that there is no optimal detumbling controller for every-case, the decision upon a detumbling controller should be adapted to the needs and requirements specific to the CubeSat.Yet, considering the need depicted on this paper for a 2U CubeSat, the lack of results from the simulation hint that further research should be conducted to determine with high confidence an optimal detumbling algorithm. Reflecting upon the obtained results and knowledge upon the previous controllers, it is crucial to explain the key strengths and weaknesses of the controllers. The Enhanced Bdot controller has the benefits of having the theoretically fastest convergence time to zero state, while sacrificing a higher final error and decrease in power efficiency. The proportional time-varying gain bdot controller provides a faster convergence to the steady-state limit cycle, closely tied to the Angular rate feedback controller. In contrast the static gain proportional bdot controller is showed to be the last to converge to a steady state limit cycle. Lastly, from the bdots controller the bang-bang bdot seems to have the fastest convergence time, sacrificing power efficiency and final error.The Angular Rate Feedback controller seems to perform the best out of the previous controllers, having an asymptotic convergence to a zero steady-state absolute angular rate. Therefore, if attitude information is available from the CubeSats gyroscope, Angular Rate feedback seems the appropriate detumbling solution, but in the case that such data is not available or limited a b-dot controller variation will be more appropriate based on the power consumption and error requirements.

VII. Appendix

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