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Designing attitude controller for nano/pico satellites at detumbling mode using magnetic sensor and actuator

Designing attitude controller for nano/pico satellites at detumbling mode using magnetic sensor and actuator

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Abstract. Recently, satellites have been becoming economically attractive in many applications using the advanced technologies and payloads. Practically, the launching process of any satellite passes through some stages under different conditions. For example, the satellite might be uncontrollable in the detumbling mode. Thus, it might be a risk of accident with space debris and the satellite can not complete the specified mission. So it is necessary to design an attitude controller to stabilize the satellite after the separation phase, i.e., in the detumbling mode. In this paper, we design an attitude controller to bring the satellite to the desired condition with a minimum angular momentum. The magnetorquers and magnometers are an effective solution for the satellite in low-Earth orbits because they are smaller and lighter than others. Simulation studies are presented to validate the proposed attitude control approaches.

1. Introduction

In recent years, satellites receive increasing economical attention due to a widespread range of possible applications, such as meteorology, communication, surveillance, and navigation satellites. Among all satellite types, the small satellites, e.g., nano, pico, cubesat, have been used to reduce the launching and development costs. Practically, the launching process passes through some stages under different conditions. For example, in the detumbling mode, the satellite might be uncontrollable after separation from the launcher. Thus, it might be a risk of accident with space debris and the satellite can not complete the specified mission. So it is necessary to stabilize the satellite in the detumbling mode to reduce the angular rates before the normal operation [1].

In the literature, many detumbling control approaches have been proposed using different actuators and sensors. For example, the B-dot controller is considered as the most commonly approach for detumbling control. A theoretical investigation, e.g., convergence properties, of the B-dot law were discussed in [1] averaging approach. Bang-Bang approach is another type of the B-dot controller which determined higher torque, thus it leads to reduce the energy efficiency. Moreover, Bang-Bang controller might not be able to detumble the satellite ever. Another feedback detumbling controller, in [2], used the satellite angular rates measurements. The asymptotic stability is proofed to zero angular velocity globally from an arbitrary tumbling condition under a time varying magnetic field. This feedback controller were able to detumble the angular velocity to zero with a faster decay. Many optimization-based controllers have been proposed such as linear-quadratic regulator [3], [4], to optimize the detumbling performance.

In this work, we design an attitude controller to bring autonomously the satellite to achieve the coarse requirements,i.e., minimum angular momentum. Typically, it is required to minimize the detumbling duration, e.g., up to 2 orbits [1]. For example, the spacecraft is detumbled in 0.13 [s] at 400 [km] in LEO orbit [5]. In the literature, detumbling controller uses active or passive actuators, e.g., magnetic actuators, reaction wheels and thruster, to apply the required torque to control the spacecraft attitude. For example, the magnetorquers are an effective actuators for the satellite in low-Earth orbits (LEO) because of saving of the complexity, cost, size, mass comparing to other types of actuators.

Actually, detumbling controller requires an accurate information about the spacecraft orientation obtained relative to a specific frame or certain object [6]. To sense the satellite orientation, there are many sensors, such as Star Trackers, Earth sensor, magnetometer, Sun sensor, GPS, and Gyros. Practically, the sensor measurements are processed through the determination algorithm, e.g., Kalman filtering, to obtain the attitude estimation. During the detumbling mode, there are specific requirements on the reliability of the proposed controller, sensors, and actuators [1]. In this paper, we propose magnetic-based attitude controllers, i.e., using magnetorquers and magnometers. Simulation studies are presented to validate the proposed attitude control approaches.

The main contribution of this work is to augment the PID controller on the B-dot controller. Therefore the modified control approach does not need extra sensor nor actuator.

Section II presents the the mathematical model for the underlying satellite. Section III illustrates the proposed controllers. Section VI discusses the simulation results of two controllers using magnetorquers and magnometers. Finally, the conclusion and the future work are presented in Section VI.

2. Satellite forces and mathematical model

This section presents the spacecraft model dynamics and kinematics, sensors information (position and velocity), and external torques (actuators), which are presented in well-known reference frames.

2.1. External disturbances

In case of pico/nano satellites, there are four main external disturbances affecting the satellite orientation, e.g., magnetic, aerodynamic, and gravity gradient disturbances as well as Solar radiation pressure effects. For example, the magnetic disturbances are mainly created when the geomagnetic field is interacted with any residual magnetization generated by electric currents. Practically, all external disturbances depend on the spacecraft status, e.g., orbital position, orbital velocity, orientation.

2.2. Mathematical model

This work proposes a detumbling controller for a 3U class CubeSat, which is specified as a rigid body with homogeneous density, see figure 1. The satellite has a weight of 3.5 [kg] and the cube dimension is 13x13x30 [cm]. The satellite attitude is represented by (θ, ϕ, ψ), where θ is rotation about roll axis, ψ is rotation about pitch axis, and ϕ is rotation about yaw axis.

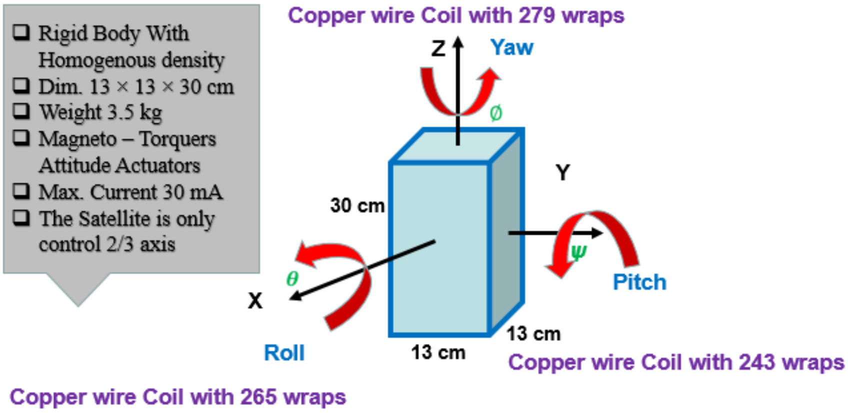


Figure 1: CubeSat Satellite model with coil magneto-torquers.

The mass distribution around the centre of mass was presented using the inertia matrix:

$$I = \int \begin{bmatrix} (x^2+z^2) & -xy & -zx \\ -xy & (z^2+x^2) & -yz \\ -zx & -yz & (x^2+y^2) \end{bmatrix} dm, \tag{1}$$
$$= \begin{bmatrix} 0.3741 & -0.005915 & 0 \\ 0 & 0.3741 & -0.01365 \\ -0.01365 & 0 & 0.1183 \end{bmatrix} [kg.m^2]$$

where m is the satellite mass, and the product inertia value was assumed to be 10% off [1].
The torque T_{ctrl} affecting on the satellite is

$$\vec{T}_{ctrl} = \vec{M} \times \vec{B}, \tag{2}$$

herein, $\vec{B}$ represents the local magnetic field, and $\vec{M}$ is the satellite magnetic moment that is created using Magnetorquers, see figure 3, to detumble the satellite. Therefore, the B-dot control can regulate the electro-magnetic dipole moment to detumble the spacecraft angular rate equal/close to zero. The resulting torque is created by passing an electric current through coils as:

$$\vec{M} = NIA\hat{n}, \tag{3}$$

where, $\hat{n}$ represents the electro-moment dipole, N is the number of coils, I is the current, and A is the coil's cross sectional area. So the resultant torque is represented by:

$$\vec{T}_{ctrl} = NIAB(\hat{n} \times \hat{b}). \tag{4}$$

Herein, $\hat{b}$ represents the unit vector of the local magnetic field.

3. Detumbling control approaches

In this paper, we design a magnetic-based attitude controller, i.e., B-dot controller to detumbling a satellite and to track a desired angular rates. In general speaking, the B-dot controller is known as a torque projection-based controller using magnetorquers and magnetometers. The main idea herein is that the magnetorquer generates a desired magnetic dipole moment

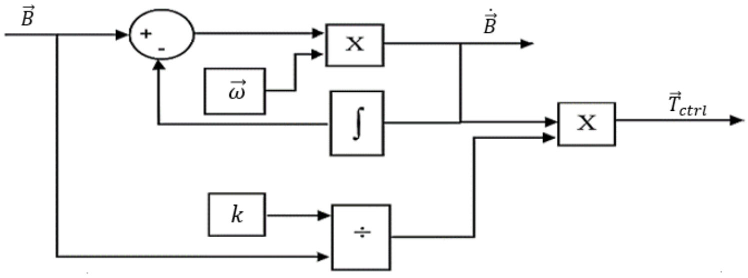


Figure 2: B-Dot Detumbling Controller.

$(m)\,[Am^2]$ proportional to the change rate of the geomagnetic field affecting on the spacecraft to restore/rotate spacecraft about the desired axis. This geomagnetic field is measured by a three-axis magnetometer and described in the body frame. This is the reason to call it B-dot controller, see figure 2.

So the resulting torque is represented as:

$$\vec{T}_{ctrl} = \frac{k}{\|\vec{B}\|}(\vec{w} \times \vec{b}) \tag{5}$$

where $\vec{b} = B/\|B\|$ and K is positive scalar gain used to determine the required torque to detumble the spacecraft as:

$$\vec{T}_{ctrl} = k(\vec{w} \times \vec{b}) \times \vec{b} = -k(I_3 - \vec{b}\,\vec{b}^T)\vec{w} \tag{6}$$

The control torque is obviously perpendicular to the local magnetic vector $\vec{b}$ [1].

To demonstrate the controller stability, we can use the candidate Lyapunov function [1]:

$$\vec{V} = \frac{1}{2}\vec{w}^T I \vec{w}, \tag{7}$$

where I is an inertia matrix represented as:

$$I\dot{\vec{w}} = -[\vec{w}]\ I\vec{w} + \vec{T} \tag{8}$$

So the Lyapunov function is represented as:

$$\dot{\vec{V}} = -k\vec{w}^T(\,I_3 - \vec{b}\vec{b}^T)\vec{w} \tag{9}$$

Herein the eigenvalues of $(I_3 - bb^T)$ are always (0, 1, 1). Therefore, the magnetic field variation is defined as:

$$\dot{\vec{B}} = A\dot{\vec{R}} - \vec{w} \times \vec{B}, \tag{10}$$

where R is the geomagnetic vector. As a result, the magnetic field variation depends on the satellite orbital position. As initial stage of detumbling, we can approximation:

$$\vec{M} = -\frac{k}{||\vec{B}||} \times \dot{\vec{B}} \tag{11}$$

The gain value k of the B-dot controller can be determined as:

$$k = \frac{4\pi}{T_{orb}}(1+\sin i)I_{min} \tag{12}$$

T_{orb} represents the orbital period [sec], I_{min} is a minimum value of the principal inertia moment, and i is the inclination angle [degree] [1, 7].

As illustrated here, the main feature is that the B-dot controller does not need to measure the satellite's angular rates [8]. However, B-dot controller might lead to a suboptimal torque vector, especially in small angular velocities, as the generated dipole moment might not be orthogonal to the geomagnetic field [8]. Therefore, we augment the B-dot controller with a proportional integral derivative (PID) controller that is expressed as

$$u(t) = K_P\dot{B}(t) + K_I\int_0^t \dot{B}(t)dt + K_D\frac{d\dot{B}(t)}{dt}. \tag{13}$$

The main aim of PID controller is to minimize the magnetic field variation $\dot{B}(t)$, that can be achieved by a proper tuning of the PID gains. For example, the proportional gain K_P is main term that affect the system response. On another hand, the integral term K_I penalizes the magnetic field variation. While the transition response is enhanced mainly by the derivative term K_D, which estimates the system response in the future considering the error rate over past time.

The basic steps in developing PID controllers can be summarized as follows:

(i) First, we obtained the open-loop and closed-loop response, then determine what needs to be improved.
(ii) We added a proportional control $K_P > 0$ to improve the rise time.
(iii) We added a derivative control $K_D > 0$ to improve the overshoot.
(iv) We added an integral control to eliminate the steady-state error $K_I > 0$.
(v) Finally, we adjusted each of K_P, K_I, and K_D until we obtained the desired detumbling response.

Typically, the main limitation of PID is that it can not handle multi-variables systems. However, the underlying system is single-input-single-output, so PID can be used efficiently.

During the detumbling mode, we take into account some factors and specific requirements on the reliability of the proposed controller, system robustness, sensors, actuators, and detumbling duration [1].

3.1. Sensors and actuators

In this work, the detumbling controller uses active actuators, e.g., magnetic actuators to apply the desired torque to control the spacecraft attitude. As mention before, the magnetorquers are more effective actuators, especially for the satellite in LEO orbits. Practically, magnetorquers have less complexity, cost, size, mass comparing to other types of actuators. Furthermore, they need low power consumption so they are more reliable for long duration, i.e., they do not degrade over time. Moreover, magnetorquers do not contain any moving element, thus it reduce the sensitivity to the large loads due to the vibration. Typically, the magnetorquers have been used to dump the angular momentum generated by external disturbances [7].

In details, an electrical current passes through a wire coil to produce an electromagnetic dipole/field that has interaction with the magnetic field of the Earth. Thus, it leads to produce the required torques to regulate the satellite's attitude. The block diagram of the magnetorquers is illustrated in figure 3. In the literature, the magnetorquers have used as main actuators for ACS or as secondary actuators only for achieving zero momentum.

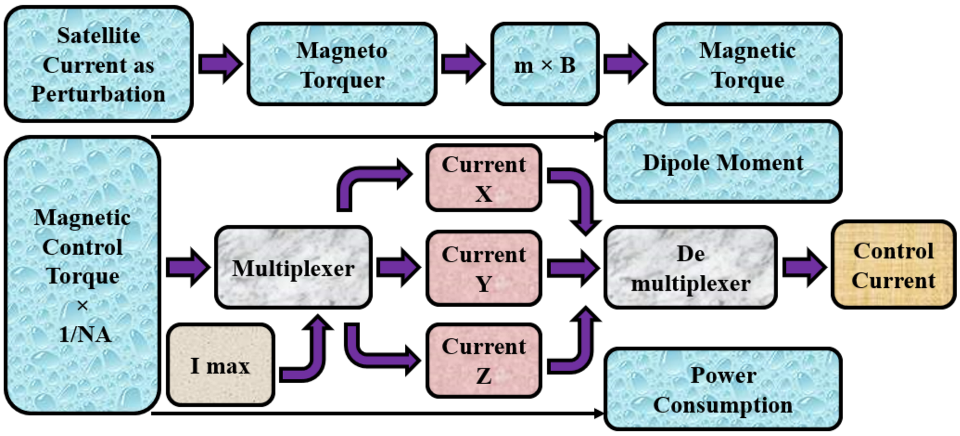


Figure 3: Satellite magnetorquer block diagram.

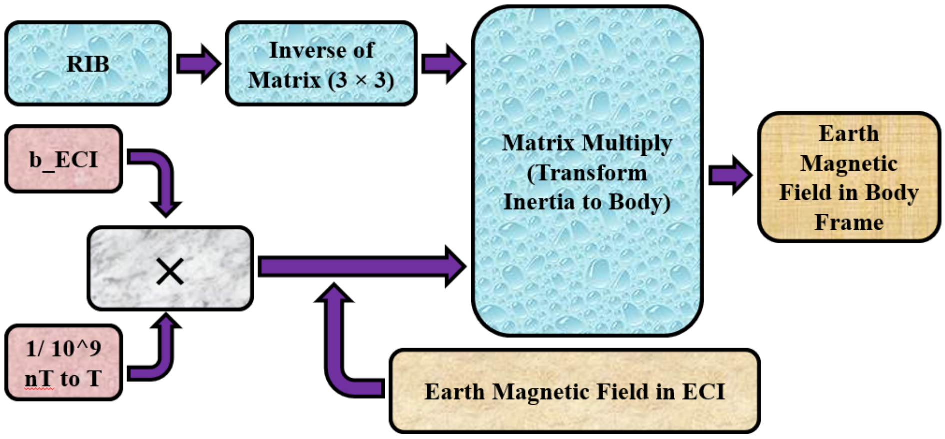
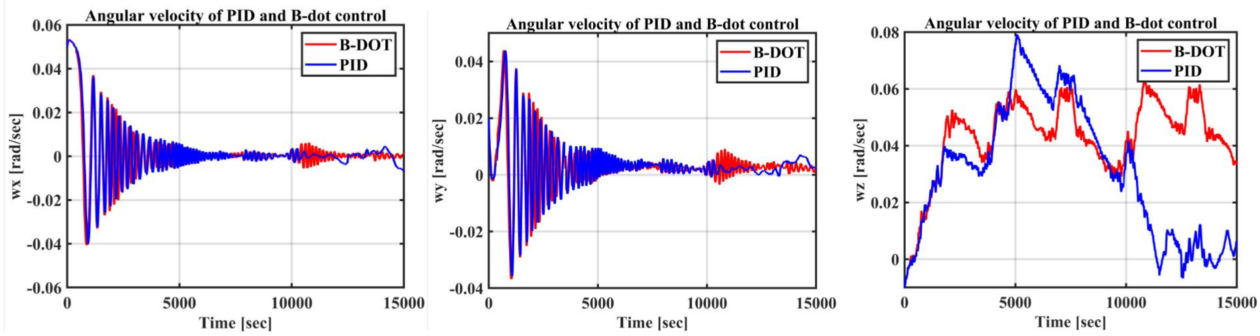


Figure 4: Satellite magnetometer sensor block diagram.

However, the magnetorquers can only control the satellite in two of three axes as these actuators only generate perpendicular torque of the local magnetic field. In case that the spacecraft is magnetically actuated and the geomagnetic field is varying, the uncontrollably of the angular dynamics might be only time-varying [1]. Therefore, many research studies have been proposed to these challenges especially in designing ACS system. In this work, the attitude actuators are proposed to be coil-type magnetorquers in a three axis configuration. The copper wire coils have 265 wraps around the x-axis, 243 wraps around the y-axis, and 279 wraps around the z-axis. The maximum current in the underlying satellite is set to be 30 [mA] [7].

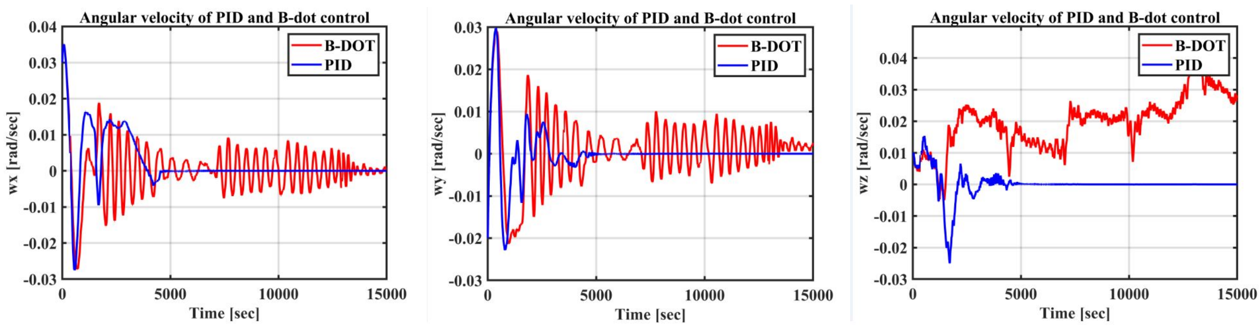
Actually, ACS requires an accurate information about the spacecraft orientation, e.g., angles, quaternion, and attitude rates, using sensors information and mathematical models. To sense the satellite orientation, there are many sensors, e.g., star trackers, Earth sensor, magnetometer, Sun sensor, GPS, and Gyros. In this work, magnetometer provides the magnetic field information used to detumble the spacecraft attitude in the LEO orbit. The block diagram of the magnetometer is illustrated in figure 4. However, the magnetometer measurements are affected by the electric current passing through other devices, e.g., actuator magnetic coils.

However, the magnetometers measurements, i.e., magnetic field, has a small value noise. For this reason, we need to apply a low-pass filter, e.g., infinite impulse response, to determine a cleaner derivative estimate.



(a) x-axis angular velocity. (b) y-axis angular velocity. (c) z-axis angular velocity.

Figure 5: Comparison between both (B-dot and PID) controllers at initial rotation angles $[\psi\,\theta\,\phi] = [0\,0\,0]$ [rad] with angular velocities $\omega_{x1} = 0.05, \omega_{y1} = 0.03, \omega_{z1} = -0.01$ [rad/s], around the axes X,Y, Z, respectively.



(a) x-axis angular velocity. (b) y-axis angular velocity. (c) z-axis angular velocity.

Figure 6: Comparison between both (B-dot and PID) controllers at initial rotation angles $[\psi\,\theta\,\phi] = [0\,0\,0]$ [rad] with initial angular velocities , $\omega_{x2} = 0.03, \omega_{y2} = 0.02, \omega_{z2} = 0.01$ [rad/s], around the axes X,Y, Z, respectively.

4. Results and analysis

To illustrate the efficiency of the proposed detumbling controllers, we consider a satellite model implemented in Simulink [7]. This work proposed a comparative synthesis of two detumbling approaches, e.g., B-dot and PID controllers, as described in Section V. Tuning the controllers gains depends mainly on the satellite specifications, e.g., mass moment of inertia, so these gains have to be retuned for another configuration.

The proportional terms, i.e., k, K_P have a crucial role in enhancing the transient response, e.g., decrease the settling (detumbling) time. On another hand, it affects the satellite stability and the magnetorquers sensitivity where the currents on the magnetorquers are restricted to a maximum of 30 [mA] to prevent large torques. According to the findings, B-dot controller can not detumble the satellite due to system instability at $k = 1x10^7$ for $t = \pm 1000$. In this work, the B-dot gain k is set to 1000 to achieve the best and smoothest result. The PID controller gains are $K_P = 10000, K_I = 100, K_D = 1000$.

The simulation results are illustrated in Figures 6. The underlying satellite is supposed to start operation initially at initial rotation angles $[\psi\,\theta\,\phi] = [0\,0\,0]$ [rad] with different angular velocities around the axes X,Y, Z, respectively $\omega_{x1}, \omega_{y1}, \omega_{z1} = [0.05\ 0.03\ -0.01]$ [rad/s], and $\omega_{x2}, \omega_{y2}, \omega_{z2} = [0.03\ 0.02\ 0.01]$ [rad/s]. As illustrated in Figures 6, both B-dot and PID controllers are capable to achieve the required performance, i.e., detumbling the satellite angular rate in short duration roughly an one orbit. In details, B-dot controllers detumbles the angular rate to less than 0.006 rad/s in duration 15000 sec which is less than one orbit period. While the PID approach achieves faster detumbling to zero angular rates in 4600 seconds. As shown in Figures 6, the satellite rotated around the X,Y, Z axes due to the initial satellite position at the equator. Moreover, the geomagnetic field is affecting on the satellite in the down direction, so it has a less effect on pitch rotation than another component in the other direction. The satellite rotated four times in the x-axis (roll) and three times in the z-axis (yaw). So a full rotation can not occur in the y-axis (pitch).

Another interesting point, the B-dot controller, during the detumbling, can not stabilize the satellite attitude entirely. It can not recover the low angular rates, so the spacecraft spins about the z-axis or yaw, see Figures 6. A possible explanation is due to the magnetic variation because the field strengthens when the satellite moves closer to the Earth's magnetic pole. The B-dot controller might need to be retuned to stabilize the spacecraft about the z-axis, however it will affect the system performance on other x, y axes. On another hand, the PID controller is able detumble the satellite attitude entirely after the detumbling mode. This happened due to the integration term which leads to eliminate the steady-state error. Another factor has to be considered during the controller design is the implementation simplicity. In principle, both controllers are simple, yet the B-dot is more simple to be implemented.

5. Conclusions and future works

This paper has proposed an augmented B-dot with classical controller implemented on a satellite on the LEO orbit. Moreover, a detailed discussion on tuning PID gains is illustrated. The simulation results indicated that the detumbling performance of PID controller responds effectively and enhances system robustness compared to the B-dot performance. Possible extensions in the future are consider a detumbling approach in three axes to achieve better performance using different sensor and actuator types.

References

[1] Lovera M. Magnetic satellite detumbling: The b-dot algorithm revisited. In: 2015 American Control Conference (ACC). IEEE. 2015, pp. 1867-1872.
[2] Avanzini G and Giulietti F. Magnetic detumbling of a rigid spacecraft. In: Journal of guidance, control, and dynamics 35.4 (2012), pp. 1326-1334.
[3] Andresen B, Grun C, Knudsen R, Nielsen K, Srensen K and Taagaard D. Attitude control system for AAUSAT-II. In: Institute of Electronic Systems, Aalborg University (2005)
[4] Foletti A and Kaewkerd P. SwissCube Phase A ADCS Report. Tech. rep. EFPL, Lausanne, Switzerland, 2006.
[5] Jonsson L. Simulations of Satellite Attitude Maneuvers: Detumbling and Pointing. MA thesis. Department of Computer Science, Electrical and Space Engineering: Space Engineering, Lulera University of Technology.
[6] Markley F and Crassidis J. Fundamentals of spacecraft attitude determination and control. Vol. 1286. New York: Springer, 2014.
[7] Muksin A, Poetro R, and Triharjanto R. Pico-satellite detumbling simulation using magnetic atitude actuator (Simulasi detumbling pada satelit piko menggunakan aktuator sikap magnetik). In: Jurnal Teknologi Dirgantara 15.1 (2017), pp. 11-20.
[8] Desouky M and Abdelkhalik O. A new variant of the B-dot control for spacecraft magnetic detumbling. In: Acta Astronautica 171 (2020), pp. 14-22.