LATIN AMERICAN CUBESAT WORKSHOP
SALVADOR, BR
OCTOBER 2024

CubeSat Detumbling Simulation Using B-dot Control Law

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Abstract

The exponential increase in CubeSat launches in recent years, particularly through university and technology programs, has sparked advancements in Attitude Control Systems (ACS), which address satellite tumbling and detumbling issues critical to mission success. A widely used control law for this is the B-dot control, which leverages the interaction between Earth's magnetic field and the magnetic field produced by current-carrying coils along three orthogonal axes to control the satellite's rotation. This method is popular for CubeSats due to its simplicity, ease of implementation, and low computational demands. This study outlines the methodology for developing this control strategy and validates its effectiveness with a MATLAB implementation on the PdQSat, demonstrating successful detumbling capabilities.

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1 Introduction

CubeSat launches, largely driven by academic institutions and technology programs, has brought attention to essential operations like Attitude Control Systems (ACS). The detumbling of satellites are critical challenges for both small and large satellites, as uncontrolled rotations can compromise entire missions. Various control methods have been studied, with the B-dot control law emerging as a popular approach for CubeSats due to its simplicity, low computational cost, and effectiveness.

CubeSats, introduced in 1999, have become popular in educational settings because they are cost-effective and allow for hands-on exploration and mission execution [1]. For a proper functioning, stabilization and orientation control post-launch are crucial; failure in these areas can jeopardize mission objectives [2]. While control systems for satellites can use different actuators, magnetorquers are preferred for CubeSats due to fewer mechanical components, lower energy consumption, and straightforward implementation [3]. However, they rely on the Earth's magnetic field and lack the precision of other methods, given variations in the magnetic field [4].

CubeSats, introduced in 1999, have become popular in educational settings because they are cost-effective and allow for hands-on exploration and mission execution [1]. For a proper functioning, stabilization and orientation control post-launch are crucial, *as a* failure in these areas can jeopardize mission objectives [2]. While control systems for satellites *can vary on use of* different actuators, magnetorquers are preferred for CubeSats due to fewer mechanical components, lower energy consumption, and straightforward implementation [3]. However, despite the advantages, they rely on the Earth's magnetic field leading to a lack of precision comparing other methods, given the variations in the magnetic field [4].

This study is part of UFMG's PdQSat project, which seeks to test a prototype lithium-sulfur battery and a new supercapacitor in orbit. To ensure data transmission back to Earth, PdQSat's control system must stabilize and orient the satellite after deployment. This paper evaluates the B-dot control law implemented with a three-axis magnetorquer configuration as a detumbling strategy, building on its effectiveness in CubeSat orientation control.

2 Methodology

This study analyzed and tested the B-dot control strategy for the PdqSat CubeSat through MATLAB simulations, following a systematic approach:

1. **Define Orbital Parameters:** The premise for a circular orbit and a set of fixed orbit configurations was based on previously analyzed scenarios [5], as shown in Table 1.

Table 1: Orbit Candidates

Incl (i) [°]	***Radius* (a) [km]**			
	6778	6878	6978	7078
10		x	x	x
20		x	x	x
30		x	x	x
40	x	x	x	x
50	x	x	x	x
60		x	x	x
70		x	x	x
80		x	x	x
90		x	x	x

2. **Satellite Body Specifications:** The CubeSat was modeled as a 3U configuration (100 mm $\times$ 345 mm $\times$ 100 mm) with a total mass of 25.0 kgf. The payload was represented as a 3.0 kgf homogeneous parallelepiped, centered within the CubeSat, while the remaining mass of 22.0 kgf was uniformly distributed in the rest of the volume. This configuration resulted in moments of inertia of $I_x = 0.0332$ kg·m^2, $I_y = 0.0335$ kg·m^2, and $I_z = 0.00444$ kg·m^2.

3. **Magnetorquer Specifications:** The magnetorquer was modeled as three air-cored coils with a cross-sectional area of 0.02 mm^2 and 2000 turns per coil, following the literature [6].

4. **Define Initial Rotation:** Initial rotation values were generated using MATLAB's

pseudo-random function, within a range of $[-1.5, 1.5]$ rad/s, and were saved for consistency across all simulations.

5. **Set and Adjust Gain Values:** The gain k was varied from 0.0001 to 0.020, with six initial values selected to establish gain limits. A 15% safety margin was applied to the minimum and maximum values to ensure robustness.

6. **Randomize Initial Velocities and Simulate:** Six random initial velocities were generated and set as initial conditions for the MATLAB program. The control strategy was then tested across all orbits listed in Table 1 to observe how variations in k affected the system's performance.

7. **Analyze System Response:** The system's behavior was assessed through three key performance metrics:

   - *Control Effort:* Calculated as the integral of the currents applied (measured in coulombs), using the trapezoidal rule.
   - *Signal Energy:* The integral of the square of the applied currents (measured in joules), also calculated using the trapezoidal rule.
   - *Integrated Absolute Variation (IAV):* This metric, representing the "smoothness" of the response, was determined by the cumulative sum of the absolute difference between successive current values.

3 Results and Analysis

Simulations were run for initial conditions as Table 2:

Table 2: Initial conditions for simulation (rad/s)

	ω_1	ω_2	ω_3
A	-0.5730	0.2492	0.4124
B	1.500	0.8052	-0.9023
C	-0.1252	-0.7429	0.3890
D	0.6652	0.5586	-0.1724
E	0.4675	0.6944	0.2488
F	0.7352	0.2860	-0.5261

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The new set of orbit candidates is shown in Table 3

Table 3: New Orbit Candidates

Incl (i) [°]	***Radius* (a) [km]**			
	6778	6878	6978	7078
10		x	x	x
20		x	x	x
30		x		x
40	x	x	x	x
50	x	x	x	x
60		x	x	x
70		x	x	x
80		x	x	x
90		x		x

The value of k for each orbit condition found is presented in Table 4.

For this paper, some results of Case A will be presented.

Table 4: Ranges of k to different orbits

Orbit Alt. (km)	Inclin. (°)	k_Min	k_Max
6778	10	N/A	N/A
	20	N/A	N/A
	30	N/A	N/A
	40	0.0067	0.0326
	50	0.0015	0.0420
	60	N/A	N/A
	70	N/A	N/A
	80	N/A	N/A
	90	N/A	N/A
6878	10	0.0007	0.0085
	20	0.0008	0.0087
	30	0.0009	0.0089
	40	0.0009	0.0092
	50	0.0010	0.0094
	60	0.0010	0.0098
	70	0.0012	0.0099
	80	0.0012	0.0100
	90	0.0012	0.0101
6978	10	0.0005	0.0077
	20	0.0012	0.0090
	30	0.0046	0.0117
	40	0.0102	0.0160
	50	0.0120	0.0257
	60	0.0059	0.0337
	70	0.0017	0.0407
	80	0.0029	0.0484
	90	0.0041	0.0544
7078	10	0.0006	0.0088
	20	0.0006	0.0093
	30	0.0007	0.0099
	40	0.0013	0.0105
	50	0.0016	0.0112
	60	0.0018	0.0118
	70	0.0021	0.0122
	80	0.0022	0.0125
	90	0.0023	0.0126

Figure 1: Case A - Oscillation in the beginning of the range.

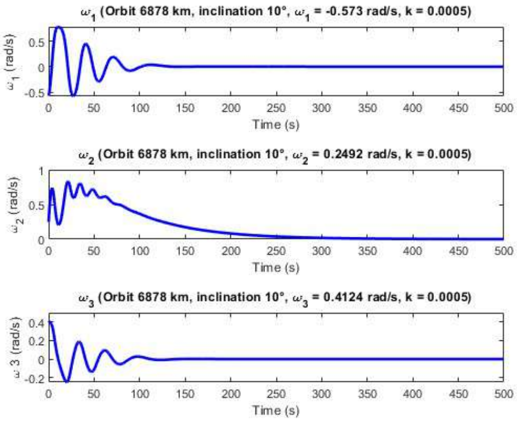


Figure 2: Case A - Oscillation in the middle of the range.

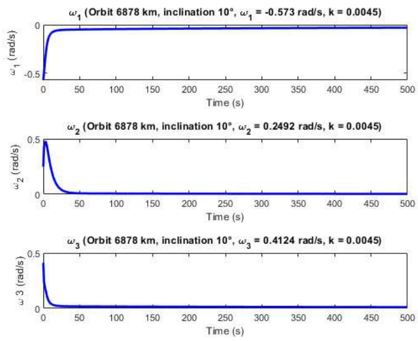


Figure 3: Case A - Oscillation in the end of the range.

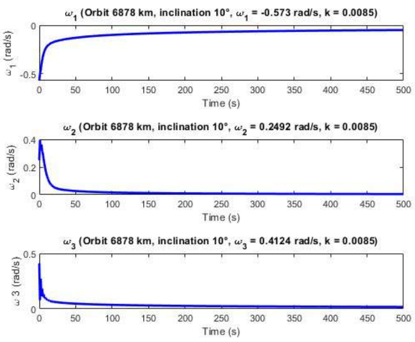


Figure 4: Case A - High values of k.

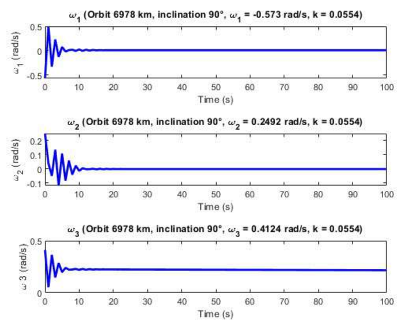
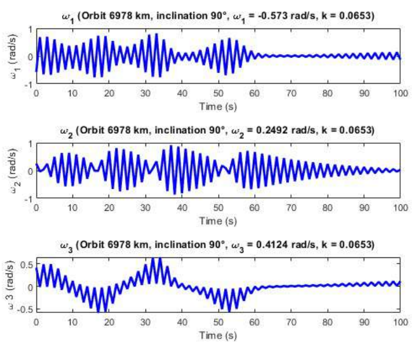


Figure 5: Case A - Controller with high velocity oscillation.



4 Discussion

The use of small increments took an elevated computational effort, but made possible to set a fine margin of gain.

Each case presented a peculiarity and made possible the observation of some characteristic of the system.

In Case A, the controller successfully managed the CubeSat's initial tumbling velocities in a 6878 km orbit with a 10° inclination. Using moderate gain values, the controller reduced oscillations and stabilized the system efficiently. As gain k increased, the system exhibited faster settling times and reduced error, although higher gains introduced slight oscillations in control signals. The results demonstrated effective detumbling at lower speeds within the target range, affirming the controller's suitability for this orbit with minimal control effort and energy consumption.

Case B did not achieve successful control due to high initial rotation speeds that exceeded the controller's operational limits. The CubeSat's low moment of inertia made it challenging for the controller to act effectively at these speeds. As a result, this case underscored the controller's limitation in handling higher velocities, establishing a practical speed range from -0.8 to 0.8 rad/s, where the controller can function effectively. This insight informed the need for initial speed constraints or adjustments in gain to ensure stability for similar cases.

As for Case C, the controller operated effectively for a 6878 km orbit at 30° inclination, demonstrating stable detumbling for moderate initial angular velocities. Similar to Case A, the control effort and signal energy were responsive to variations in the gain k; lower gains resulted in smoother oscillations but higher settling times, while increased gains reduced settling time but introduced minor control signal fluctuations. Overall, the case confirmed that the controller maintains stable detumbling at moderate gain values, with control effort and energy remaining within acceptable levels, validating the controller's functionality for this orbital setup.

In Case D, the controller effectively stabilized the CubeSat's angular velocities within the tested gain range for an orbit of 6978 km and an inclination of 90°. The control effort and signal energy varied with system oscillations rather than initial speed, requiring slightly more effort due to axis-specific oscillations. Increasing the gain k initially improved stabilization by reducing settling time and error, but excessive gain led to increased oscillations and control signal variability. This case highlighted the need for careful gain tuning, especially as higher gains at this altitude and inclination introduced errors that slowed the detumbling process. Nonetheless, the controller demonstrated reliable long-term detumbling capability with moderate gain values.

In Case E, the controller was tested in a 6978 km orbit with a 60° inclination, where it encountered significant oscillations due to higher initial angular velocities. This case required more control effort and signal energy than previous cases, as the oscillatory behavior demanded higher adjustments to stabilize the CubeSat. The results indicated that although the controller could eventually reduce the tumbling, higher initial velocities in certain orbits increase the control effort and energy consumption significantly. This case highlights the sensitivity of the controller to initial conditions and demonstrates that higher inclinations may require further tuning to minimize oscillations effectively.

Case F involved a 7078 km orbit at a 70° inclination, with initial angular velocities slightly higher than in Case E. The controller effectively managed the CubeSat's detumbling, but this required substantial control effort and signal energy, especially on the z-axis. Similar to Case E, the results demonstrated that higher inclinations and velocities increase the demand on the controller, impacting the smoothness of the control response. Despite this, the controller was successful in stabilizing the CubeSat within the expected range, though energy consumption was notably higher. This case emphasizes the need for careful gain tuning in high-inclination orbits to achieve stability without excessive energy expenditure.

Almost all family of analized orbits are shown to be suitable within the gain range for the tested initial conditions. The controller did not achieve good results for two orbits, both with radius 6978 km and inclinations 30° and 90°. This does not mean that such orbits cannot be used, but need further studies. For simplicity, those orbits were discarded, with next steps evaluated for the remaining ones.

5 Conclusion

The conclusion of this study demonstrates that detumbling a 3U CubeSat with similar mass properties to PdQSat can be achieved using lightweight actuators, such as three-axis orthogonal magnetorques, and a simple control law like the B-dot. The controller effectively stabilized the CubeSat, reducing its tumbling to near-zero values, though limitations were identified with high initial speed conditions due to the satellite's moment of inertia. Issues, such as the one encountered at 6978 km and 50° inclination with a specific gain value, highlighted the need for manual tuning of the controller, as the gain calculation formula found in the literature [6] did not yield satisfactory results in all cases. Despite these limitations, the B-dot controller proved effective for PdQSat in most tested orbits, though orbits at 6978 km with 90° and 30° inclinations are less suitable due to system behavior and high control energy consumption, respectively. Future work is suggested to further optimize controller tuning, explore energy consumption across various conditions using techniques like Monte Carlo simulations, and select the most energy-efficient orbits for the PdQSat mission based on mission requirements.

References

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