Optimizing CubeSatellite Orientation Using Magnetorquers

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1. Executive Summary[1]

This white paper presents a comparative study of magnetorquer-based attitude control solutions for 1U CubeSatellites (CubeSats), with an emphasis on initial detumbling following deployment into Low Earth Orbit. CubeSats experience very high initial angular velocities due to spring-loaded ejection mechanisms in their launch vehicles, often reaching 10–20°/s. To stabilize these small satellites efficiently under strict power, mass, and volume constraints, magnetic actuators known as magnetorquers are utilized. Their application is examined in this white paper.

The analysis begins by outlining three main types of magnetorquers(air-core coils, embedded (PCB) coils, and ferromagnetic rod-core coils) that are compared across various parameters such as mass, torque generation, integration complexity, and power consumption. Control laws such as B-dot, bang-bang, and proportional-derivative (PD) are then evaluated for their ability to bring the spacecraft from a tumbling state to a stable orientation.

Using realistic assumptions and experimental values for Earth's magnetic flux, satellite inertia, actuator dipole strength, etc., the three configuration models are constructed and simulated. Results suggest that rod-core magnetorquers paired with a bang-bang controller offer the fastest detumbling performance within feasible power budgets, stopping the rotation in under 20 seconds.

Based on these findings, the recommended system for a resource-limited CubeSat prioritizes a **3-axis rod-core magnetorquer array controlled by a hybrid bang-bang and B-dot scheme**. This configuration achieves a practical trade-off, i.e., it maximizes torque-per-watt, requires minimal onboard sensing, and avoids moving parts, all while enabling fast, autonomous detumbling with minimal software complexity.

[1] An earlier version of this conceptual brief was documented within the One Young India student records (2025).

2. Introduction

CubeSats have revolutionized access to space by standardizing satellite-making parameters into compact 10 cm^3, 1.33 kg units (1U satellites)[1]. In order to place them in orbit, these satellites are ejected by PPOD *(Poly-Picosatellite Orbital Deployer)* springs (from the launch vehicle) with uncontrolled initial attitudes and angular rates often exceeding 10–20 °/s [2]. Without reliable stabilization, essential functions like solar array alignment, antenna deployment, and stable imaging cannot be executed. Conventional actuators such as reaction wheels and control-moment gyros offer decent pointing but incur exorbitant mass, power usage, and other complexities for a 1U satellite. By contrast, magnetorquers generate a controllable magnetic dipole that interacts with Earth's geomagnetic field to produce torque without any propellant or moving parts, making them specially suited to detumbling and coarse pointing under strict resource constraints.

3. Definitions

• Attitude (R): The orientation of the satellite body relative to an inertial reference frame, often represented using rotation matrices of quaternions.

• Magnetorquer: A magnetorquer, or magnetic torquer, is a device used in spacecrafts for attitude control and detumbling. They utilize magnetic coils, placed with respect to Earth's geomagnetic field, to generate necessary torque for detumbling/attitude control functions.

• Angular Velocity (ω): The rate at which a satellite's orientation changes over time; it is measured in radians per second.

• Detumbling: It is the process of reducing the initial uncontrolled angular motion of a satellite to near-zero rotational velocity post-deployment.

• Magnetic Dipole Moment (m): A vector that quantifies the strength and direction of a magnetorquer's field, given by $m = nIA$, where n is the number of turns, I is current, and A is the coil area.

• Torque (τ): It is the turning force generated by the interaction of the magnetic dipole with Earth's magnetic field, described by $\tau = mB$, where m is the Dipole moment and B is Earth's magnetic field.

• Geomagnetic Field (B): It is the Earth's magnetic field, which ranges from 25 to 65 μT in Low Earth Orbit (LEO).

4. Literature Review

One of the earliest and most widely cited control methods for CubeSats is the *B-dot controller*. Mark L. Psiaki demonstrated that this approach—which uses the rate of change of the magnetic field ($\frac{dB}{dt}$) to decide the direction of the magnetic dipole—can slow down a spinning satellite without needing to estimate its exact orientation. His analysis exemplified that this method naturally stabilizes the spacecraft's rotation over time. [3]

Leomanni, in his paper, exemplified a faster method called *bang-bang control*. In this approach, the system switches the magnetic dipole directly to its maximum or minimum strength depending on the direction of the change in the magnetic field. This provides much stronger and quicker torque, helping the satellite slow down its spin faster than the regular B-dot method. At low spin rates, the abrupt on-off nature of this method can cause the satellite to oscillate rather than settling steadily. To prevent such oscillations, a small threshold known as a deadband is introduced, during which no torque is applied if the angular velocity is below a certain limit. Alternatively, the system can start with bang-bang control and then automatically switch to the gentler B-dot method once the satellite slows down enough. [4]

Another method, described by Wertz (2001), is PD (*Proportional-Derivative*) control. This method allows not only detumbling but also coarse pointing—for example, aligning the satellite's solar panels' side to face the Sun. It calculates the required torque based on the current rotation rate and the difference between current and desired orientation and then applies a dipole that tries to match this torque. Since magnetorquers can only create torque perpendicular to the Earth's field, the calculated torque is projected onto the perpendicular plane. PD control gives more precise pointing but depends on knowing the satellite's attitude, which requires extra sensors like sun sensors or star trackers and complex algorithms like Kalman filters. [5]

Review papers by Bellini (2012) and the UPC Thesis by Salamat et al. (2024)compare other magnetorquer hardware designs, highlighting trade-offs in dipole strength per watt, mass density, and integration ease. Air-core and PCB coils offer minimal mass at low torque, while rod-core coils deliver the highest dipole moment density but require demagnetization cycles to prevent core saturation.

5. Attitude Control Problem

CubeSats, particularly 1U CubeSats, require onboard attitude control like magnetorquers to orient critical systems such as antennas, solar panels, or imaging instruments. Upon deployment from the launch vehicle, these satellites typically enter an uncontrolled tumbling state, with angular velocities around 10–20°/s [1] and unpredictable spin axes.

The initial and primary task of the Attitude Determination and Control System (ADCS) is to stop this rotation—referred to as detumbling—and bring the spacecraft to a stabilized state from which it can perform mission-specific pointing maneuvers. Once detumbled, the ADCS can maintain or deliberately alter the satellite's orientation based on mission objectives.

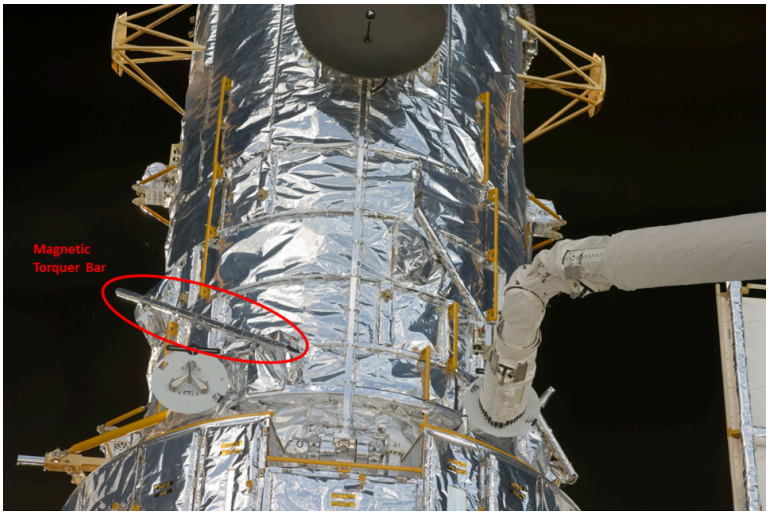
Magnetorquers are the most widely adopted actuators for early-stage CubeSat ADCS due to several practical advantages.[6] These include their low mass, absence of moving parts, and the fact that they utilize no propellant. Magnetorquers generate a magnetic dipole moment, m, which interacts with Earth's geomagnetic field, B, to generate torque via the cross product: $\tau = m \times B$ This reorients the spacecraft.

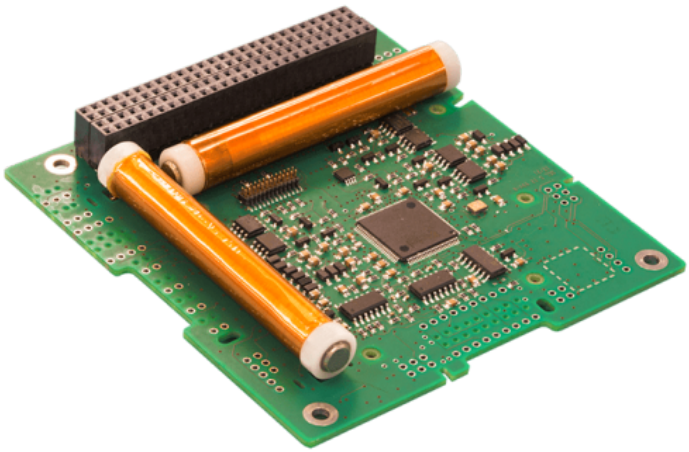
In Low Earth Orbit (LEO), typically at altitudes ≤ 500 km, Earth's magnetic field strength ranges from approximately 30 μT to 50 μT. This field provides sufficient flux density for the magnetorquers to generate the necessary torques. However, outside LEO—such as in deep space or interplanetary trajectories—magnetorquers are generally ineffective due to the lack of a stable external magnetic field, necessitating alternative actuators such as reaction wheels, control moment gyroscopes, or cold gas thrusters.[7]

For the detumbling phase, simple and robust algorithms such as the B-dot controller are frequently employed. These controllers passively align the magnetic dipole in a direction that opposes the satellite's angular velocity by responding to changes in the magnetic field vector over time, effectively damping the rotation. This does not require precise attitude knowledge—as explained by Psiaki(2001)— only time derivatives of magnetometer measurements.

In summary, CubeSat ADCS must quickly damp post-launch tumble, then maintain or change orientation under power/weight limits; magnetorquers offer a reliable, no-fuel method for the detumbling and coarse pointing stage

6. Magnetorquers: Principle & Action





fig(1) Magnetorquer on the Hubble Telescope

fig(2) Magnetorquer

A magnetorquer is simply an electromagnetic coil (often wound around a ferrite or alloy core) that produces a magnetic dipole m when current flows. The dipole interacts with Earth's field B, generating torque $\tau = m \times B$, where, $m = n \cdot I \cdot A$ for an air-core coil . The resulting torque τ tries to align the coil's dipole with the field. By adjusting currents on three orthogonal/perpendicular coils (or rods), one can produce torques about the two axes perpendicular to the local B-vector (the torque is zero if $m||B$).

Magnetorquers are widely used in small satellites because they are light and reliable [5] . They draw only electrical power (no propellant) and have no rotating parts, so in principle they can operate indefinitely if power is available . However, the disadvantages are that they can produce only weak torques (because Earth's field is weak), so attitude changes are relatively slow.

Also, the maximum torque is limited by coil current and material saturation. Thus magnetorquers are best for coarse control (detumbling) rather than fast maneuvers or precision pointing.

For a typical 1U CubeSat (inertia $\sim 0.002\ kg \cdot m^2$) in LEO, a magnetorquer dipole of $\sim 0.1\ A \cdot m^2$ interacting with $\sim 50\ \mu T$ gives $\tau \approx 5 \times 10^{-6}\ N \cdot m$, yielding an angular deceleration $\sim 2.5 \times 10^{-3}\ rad/s^2$. This can stop a 10°/s tumble in order-10^2 seconds (minutes). By contrast, an air-core coil with only $0.01\ A \cdot m^2$ dipole would decelerate ~10× slower. In practice, small CubeSats often carry 2–3 magnetorquers (one along each body axis) to allow 3-axis control. [8]

7. Common Magnetorquer Types

There are 3 main types of CubeSat magnetorquers: air coils, embedded PCB coils and rod-core(torque rod) coils. All use the same $m = n \cdot I \cdot A$ principle but differ in materials, performance and mass. It is essential to understand these types and their algorithms(next section) in order to find the most suitable one for 1U CubeSats.

1. **Air-core coils:** These are simple wound wire loops around a non-magnetic frame . Air-core coils can achieve moderate dipole moments with relatively low weight (just wire). They are easy and cheap to make (wire winding may even be manual) and are often mounted on satellite panels [9]. For a given volume, an air-core coil produces moderate torque. However, achieving a high m requires many turns or high current (increasing resistance and power). As Bellini et al. [10] note, oversizing dipole (large n, I, A) quickly increases both mass and power demand.



fig(3) Air-core coil

2. **PCB (embedded) coils**: For this, copper traces are printed onto the satellite's circuit boards or panel PCBs, forming a flat spiral coil. This uses space efficiently (the coil is built into the existing structure), so it adds almost no additional volume [11]. A PCB coil is thin (board thickness ~0.5– 1 mm), so its area and number of turns are limited, making its magnetic dipole much smaller than an equivalent 3D coil . Multiple PCB layers can be stacked to increase dipole, but manufacturing multi-layer magnetorquers is expensive [12]. Embedded coils have the advantage of integration (no extra mounts or screws) , and very low added mass (just the copper and board). However, as a disadvantage, they require high current (and thus significant power) for relatively little torque. [11]

3. **Rod-core coils:** Also known as magnetic torque rods, rod-core coils are wire coils wound around a ferromagnetic core (e.g. iron). The core amplifies the magnetic field of the coil, greatly increasing the dipole for a given current. As Benini et al. note, a torque rod can generate a "dipole considerably higher" than air-core coils [10]. In practice, rod-core torquers achieve the highest torque-per-power of the three types. For example, CubeSat hardware vendors note that a ferromagnetic rod "produces an amplification effect over an air-core magnetorquer," allowing the same torque with much less current. The trade-off is weight and



fig(4): Rod-core

complexity: the core is heavy (often tens of grams), and it retains some residual magnetization when current is off (requiring a demagnetization cycle). As Bellini et al. report, a torque-rod's metal core contributes a large fraction of its mass 16 . Also, beyond a saturation flux density the core's benefit levels off. [10]

Performance summary: This summary displays all the logical and summative conclusions from the above analysis, and is pivotal in understanding advantages and disadvantages.

1. In terms of torque output, Rod-core offers more torque than air-core, and PCB coils give the least.
2. In terms of mass and ease of fabrication, PCB coils are better than air-cores, while rod-cores come last.
3. Rod cores give high torque at low power, but add significant mass and require demagnetizing.
4. Air-core coils give moderate torque and medium power consumption, with low added mass.
5. PCB coils give the least torque (thin traces) and thus need very high current or many layers (driving up power and cost), but they save physical volume and structural mass by integration. (See Table 1 for a qualitative comparison.)

	Rod-core coils	Air-core coils	PCB coils
Mass	-	+/-	+
Torque	+	+/-	-
Power consumption	+/-	+/-	-
Ease-of-integration	-	+/-	+

table(1): Qualitative comparison of magnetorquer types

8. Control Algorithms for Magnetorquers

Now that we have established how magnetorquers work and what are the different types of magnetorquers suitable for CubeSats, we need to understand the best algorithms to make them work. Just having magnetorquers isn't enough as we need control algorithms to decide when and how to activate them. This section discusses three key control strategies used with magnetorquers.

1. **B-dot(or $\dot{B}$) control:** As mentioned in the literature review, this algorithm is one of the simplest and effective ways to stop tumbling and spinning off a CubeSat. It mainly works by detecting how fast the magnetic field around the satellite is changing($\frac{dB}{dt}$). If the field is changing in a particular direction, it denotes that the satellite is spinning. The controller then generates a magnetic dipole in the opposite direction to slow down the spin. In more technical terms, this algorithm measures the time-rate-of-change of the body-frame magnetic field. Since $\frac{dB}{dt}$ is proportional to the satellite's angular velocity, commanding a dipole opposite to $\frac{dB}{dt}$ damps rotation. This algorithm automatically steers the satellite toward aligning m and B, thereby gradually zeroing the spin. This algorithm is widely used as most small satellites employ a B-dot variant for initial detumbling [3]. The B-dot algorithm does have its disadvantages: it damps any rotation regardless of orientation, but cannot actively drive a specific attitude once stopped (and it can oscillate if poorly tuned). It works best at only high spin rates (large $\frac{dB}{dt}$).

2. **Bang-bang control:** This is a more aggressive version of B-dot control. It applies the maximum torque instantly when the magnetic field is changing beyond a certain rate. It is a form of on/off control, where each coil is driven at its maximum (saturated) current in whichever direction is required to reduce rotation. For example, a "B-dot bang-bang" law simply uses sign of $\dot{b}$ to drive maximum opposite torque [4]. Bang-bang is extremely simple to implement (just switch on/off), and maximizes deceleration (fastest detumble for a given actuator). Its major disadvantage is that it can overshoot or induce oscillation near zero velocity, and it yields jerky motion. It may also excite structural modes. Another disadvantage is that when the satellite is nearly stable, applying full torque back and forth can cause it to "wobble" instead of settling. This is known as limit cycling. In practice one might use bang-bang only until the spin drops below a threshold, then switch to regular B-dot or PD(next sub-section).
3. **Proportional-Derivative (PD) control:** The main goal of PD is to stop detumbling and to point the satellite in a desired direction. So, a PD controller requires a desired attitude (from sun/star sensors) and gyroscopic feedback. Once it calculates the desired torque, it

will apply that torque using its actuators — in this case, magnetorquers. However, because magnetorquers can only create torques perpendicular to Earth's magnetic field (B), the PD algorithm must project the desired torque onto the plane $\perp B$ [3] . Once the CubeSat has stopped tumbling, its direction can now be stabilized using PD. However, this is more complex, because PD requires a full attitude estimate. This usually means that the satellite requires a Sun sensor, a magnetometer, a gyroscope, and a more sophisticated microcontroller. This makes PD more sophisticated and harder to implement. In summary, PD control can maintain or reorient attitude after detumble, but is usually not used for the initial tumbling phase due to its complexity and need for orientation knowledge.

Other algorithms: There are several other satellite ADCS algorithms like LQR(Linear Quadratic Regulator, Quaternion Controls, Feedback linearization, etc. However, these algorithms are too complex compared to the aforementioned 3 algorithms, for usage in 1U satellites.[13] Therefore, their discussion will be omitted from this whitepaper.

9. Comparative Configuration Analysis

Here is an analysis of three hypothetical 1U CubeSat ADCS configurations (each with 3-axis magnetorquers) and compare their expected detumbling performance and complexity:

1. **Three-axis air coil with B-dot controllers:** This comprises simple coils on each body axis, driven by a standard B-dot law. Air-core coils achieve a dipole on the order of $\sim 0.01\text{–}0.1\ A \cdot m^2$ each, a value which is a practical design range. [14]

   In Low-Earth Orbit ($|B| \approx 4\times10^{-5}\ T$), a $0.05\ A{\cdot}m^2$ coil yields maximum torque of $\tau \approx 2\times10^{-6}\ N{\cdot}m$. For a CubeSat inertia $\sim 0.002\ kg{\cdot}m^2$, this gives angular deceleration $\sim 1\times10^{-3}\ rad\ s^{-2}$. Thus a hypothetical 10°/s initial spin (~0.175 rad/s) would take ~175 s to arrive at zero (order of minutes). Higher currents or more coil turns will proportionally speed this up, at cost of more power and weight. In summary, this configuration gives moderate detumble time (minutes) and low hardware complexity, but may struggle if the initial spin is very high. Power draw is low-to-moderate.

2. **Three-axis ferromagnetic torque rods with bang-bang control:** Here we replace each coil with a small rod-core (e.g. permalloy rod) of similar size. Rods can easily achieve m $\sim 0.1\text{–}1\ A{\cdot}m^2$ for the same current, so torque is ten to a hundred times higher than air-core. For instance, a rod "produces an amplification effect" allowing the same torque with far less current [15] . If $m = 0.5\ A{\cdot}m^2$, then $\tau \approx 2\times10^{-5}\ N{\cdot}m$ and deceleration would $\approx 1\times10^{-2}\ rad\ s^{-2}$. So, stopping 0.175 rad/s (a hypothetical 10°/s initial spin) takes only

~17 s. However, some drawbacks are that rods are heavier (a few tens of grams each), and require a demagnetizing cycle to reset residual field. But in terms of performance, this option greatly outpaces the first one.

3. **Three-axis embedded (PCB) coils with PD control:** As a contrasting case, we consider only PCB coils (low dipole) and a PD scheme. PCB coils may only achieve $m \approx 0.005\ A \cdot m^2$ unless many layers are used. This gives very small torques ($\tau \approx 2 \times 10^{-7}\ N \cdot m$) and thus slow detumble (hundreds of seconds). On the other hand, a PD controller could then use sensor data to point the spacecraft precisely once spin is low. This combo might minimize additional structure mass, but at the cost of very long detumbling times and complex sensing. For detumbling alone, this configuration is inferior because the weak coils and non-damping PD law would likely take far longer to shed momentum.

Analytical trade-offs: Option (2) produces by far the highest torque-to-power ratio (thanks to the magnetic core), enabling detumbling in tens of seconds. Option (1) is slower but simpler and Option (3) is least effective for detumbling. All configurations assume 3 coils (full 3-axis control).

Equations and assumptions: We recall $\tau = m \times B$, with $m = nIA$. In all cases we assume Earth's field $\sim 4 \times 10^{-5}\ T$ in LEO and a CubeSat moment of inertia $\sim 2 \times 10^{-3}\ kg \cdot m^2$.

The outputs of these simple models match published data[16].

10. Recommended Pairing

For a 1U CubeSat with an aim for low complexity and reliable detumbling in LEO, we recommend **3-axis rod-core magnetorquers with a B-dot (or bang-bang) controller.** This pairing maximizes simplicity and robustness:

Magnetorquer choice: A small ferromagnetic "torque rod" (vacuum or alloy core) coil on each axis provides the largest magnetic moment per watt [15]. Despite a slight mass penalty, the high torque means detumbling can be done quickly under realistic power limits [10]. The residual magnetism can be handled by a simple demagnetization pulse after detumble, which adds only a little complexity.

Control law: A B-dot law (or its bang-bang variant) requires only a magnetometer input and applies a straightforward damping torque. B-dot is proven for CubeSat detumble [3] and is very simple to implement in on-board software. By contrast, PD control would require full attitude estimation (sun/star sensors) and careful tuning which is an unnecessary complication for initial

detumbling. Bang-bang is even simpler (just switching coils fully on/off) and could be used at high spin rates for fastest damping, switching to B-dot for final settling.

Ultimately, this simple system offers a good trade-off of detumble speed, reliability (no moving parts), and minimal software complexity.

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