

Basic Building Blocks of Attitude and Orbit Control System (AOCS) for a CubeSat

Muddada Dhilleswararao¹, P. Mallikarjuna Rao²

¹M.Tech (Control System Engineering), Department of Electrical Engineering, Andhra University College of Engineering, Andhra University, Visakhapatnam – 530003, Andhra Pradesh, India

²Professor and Thesis Guide, Department of Electrical Engineering, Andhra University College of Engineering, Andhra University, Visakhapatnam – 530003, Andhra Pradesh, India

Abstract - CubeSats require accurate attitude control to point instruments, antennas and solar panels, yet are severely constrained in mass, volume and power. Magnetorquers meet these constraints because they generate control torque from Earth's magnetic field without consumables or moving parts. This paper presents the design, electromagnetic modeling and closed-loop simulation of a magnetorquer rod for the Attitude Determination and Control System (ADCS) of a 3U CubeSat, using a 1K107 FINEMET nanocrystalline core selected for its high permeability, near-linear B-H response and low remanence. Analytical magnetic-circuit and coil models yield a rod that delivers a magnetic dipole moment of about 0.20 A-m² from roughly 800 turns of AWG-28 wire on a 95 x 10 x 10 mm stacked-ribbon core, producing a peak torque near 8 micronewton-metres in a 40 microtesla field, five to ten times the environmental disturbance torques on a 3U bus. Finite-element analysis reproduces the analytical dipole within 2 to 5 percent, and laboratory measurements on a prototype give 0.177 to 0.181 A-m² at plus or minus 0.5 A, with an inductance of about 32.9 mH and a resistance of about 4.62 ohm, close to prediction. A full B-dot detumbling sequence is then simulated: starting from a worst-case tumble of 7.5 deg/s, the designed rod removes about 76 percent of the rate magnitude, most of it within ten minutes, with the commanded dipole bounded by the saturation limit of 0.155 A-m² and the core remaining in its linear region. The results validate the actuator at component and system level.

Key Words: CubeSat, Attitude Determination and Control System (ADCS), Magnetorquer, FINEMET 1K107 Nanocrystalline Core, B-dot Detumbling, Magnetic Attitude Control, Low Earth Orbit

1. INTRODUCTION

Small-satellite technology has reshaped Earth observation, space science and commercial space access over the past two decades, and the CubeSat built from standardized 10 cm cubic units has become its most widely adopted form. The success of any CubeSat mission depends on its ability to control its three-dimensional orientation with respect to the Earth, the Sun and inertial space, which is the task of the Attitude Determination and Control System (ADCS). Without adequate attitude control a

CubeSat cannot point a camera, hold a communication link, or keep its solar panels illuminated.

Attitude-control hardware developed for large spacecraft assumes redundant sensors, high-authority actuators and generous power, none of which is available on a CubeSat, where the entire ADCS is typically limited to a few hundred grams and a few watts. Magnetorquers have therefore become the preferred CubeSat actuator: they generate a commanded magnetic dipole that interacts with the geomagnetic field to produce torque, consume no propellant, contain no moving parts, and are inherently reliable over long low-Earth-orbit (LEO) missions.

Conventional magnetorquer cores, however, use ferrites or iron-nickel alloys whose performance is limited by low saturation flux density or by significant hysteresis, temperature sensitivity and non-linearity. Nanocrystalline soft-magnetic alloys such as 1K107 FINEMET offer a compelling alternative, combining very high permeability (of order 10⁵), a near-linear B-H characteristic, low coercivity and low remanence with good thermal and radiation stability. Exploiting these properties within the strict form factor of a CubeSat requires a systematic design method rather than empirical trial and error.

This paper condenses and reports such a method. Its contributions are: (i) selection and justification of a 1K107 FINEMET nanocrystalline core for a 3U-class magnetorquer rod, supported by a comparison with permalloy; (ii) a complete analytical model linking core geometry, coil parameters and material properties to dipole moment, torque, inductance, resistance and thermal load, with a worked 3U design example; (iii) finite-element and laboratory validation of the resulting rod; and (iv) a closed-loop simulation of the full B-dot detumbling sequence in which the designed rod is the sole actuator, quantifying the detumbling time and the actuator duty cycle that drive the electrical and thermal design.

The remainder of the paper is organized as follows. Section 2 reviews ADCS fundamentals and actuator selection. Section 3 presents the magnetorquer principle and the core-material choice. Section 4 develops the mathematical model and the design calculations. Section 5 describes the control architecture in which the rod

operates. Section 6 reports the simulation results, and Section 7 concludes with the validation outcome and the future scope.

2. ADCS BACKGROUND AND ACTUATOR SELECTION

2.1 Function and Components of the ADCS

The ADCS manages a spacecraft's attitude relative to reference frames such as the Earth-Centered Inertial (ECI), the Local-Vertical-Local-Horizontal (LVLH) and the body frames. It comprises attitude determination, which estimates orientation from onboard sensors, and attitude control, which computes and applies the torques needed to reach or hold a commanded orientation. Because no single sensor is complete, magnetometers, sun sensors, MEMS gyroscopes, star trackers and inertial measurement units are fused typically with an Extended Kalman Filter (EKF) or deterministic TRIAD/QUEST initialization into a single drift-corrected attitude estimate.

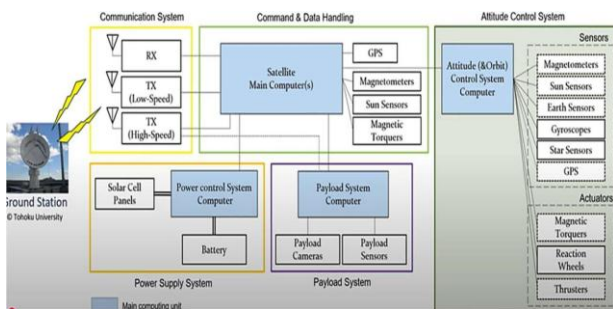


Fig -1: Block diagram of the Attitude Determination and Control System, showing the sensor-estimator-controller-actuator loop.

2.2 Attitude Representation

Three parameterizations are common. Euler angles are intuitive but suffer from gimbal-lock singularities; the direction cosine matrix (DCM) is an explicit 3×3 orthonormal rotation but carries nine constrained parameters; quaternions use four parameters, avoid singularities and are computationally efficient, which makes them the preferred representation for onboard estimation and control. Table -1 summarizes the comparison.

Table -1: Comparison of Attitude Representation Methods

Method	Parameters	Singularities	Typical use
Euler angles	3	Yes (gimbal lock)	Human interpretation, small rotations
Quaternions	4	None	Most spacecraft control and sensor fusion
DCM	9 (constrained)	None	Coordinate transformations, sensor-data fusion

2.3 Actuator Selection

Reaction wheels give precise, continuous three-axis torque but add moving parts and saturate, requiring momentum unloading; thrusters and control-moment gyroscopes provide high torque but are too complex or heavy for CubeSats. Magnetorquers, by contrast, are simple, low-mass, reliable and consumable-free, at the cost of producing torque only perpendicular to the local field and of comparatively low magnitude. For a resource-constrained 3U bus especially for detumbling and momentum management the magnetorquer is the natural choice and is the actuator developed here. Representative 3U ADCS requirements are collected in Table -2.

Table -2: Representative 3U CubeSat ADCS Requirements

Parameter	Typical value/range	Notes
Pointing accuracy	$\pm 0.01^\circ$ to $\pm 5^\circ$	Mission-dependent (imaging vs. comms)
Attitude stability	$0.1^\circ/\text{min}$ to $1^\circ/\text{min}$	Steady pointing
Slew rate	$0.1^\circ/\text{s}$ to $1^\circ/\text{s}$	Reorientation maneuvers
Detumbling time	< 2 orbits (~90 min)	Post-deployment damping
ADCS power	< 3 W	Whole subsystem
ADCS mass	< 500 g	Sensors + actuators + electronics
Lifetime	Months to years	Under LEO thermal/radiation environment

3. MAGNETORQUER PRINCIPLE AND CORE-MATERIAL SELECTION

3.1 Working Principle

A magnetorquer rod is a coil of N turns wound on a soft-ferromagnetic core. A coil current I produces a magnetic dipole moment m aligned with the rod axis,

$$m = N I A \mu_{\text{eff}} \quad (1)$$

where A is the core cross-sectional area and μ_{eff} the effective relative permeability. This dipole interacts with Earth's field B to generate the control torque

$$\tau = m \times B, \quad |\tau_{\text{max}}| = m B \quad (2)$$

About the spacecraft center of mass. Three orthogonal rods provide three-axis authority; because the torque is always perpendicular to the local field, no torque can be produced about the instantaneous field direction, but the rotation of the field over an orbit makes all axes controllable in an average sense. Sign-reversible current, driven by pulse-width modulation (PWM), sets the magnitude and direction of the torque.

3.2 Core-Material Comparison

The core material governs how efficiently coil current is converted into dipole moment. The ideal core has high permeability, high saturation induction, low coercivity, low remanence and minimal hysteresis loss. Permalloy (FeNi) offers high initial permeability (80,000–100,000) and saturation of 1.2–1.55 T but suffers hysteresis, temperature sensitivity and non-linearity. The 1K107 FINEMET nanocrystalline alloy, with 10–30 nm grains formed by annealing amorphous ribbon, provides comparable or higher effective permeability with a near-linear B–H curve. Reported comparisons show FINEMET rods with about 32 % lower hysteresis loss than FeNi50, permeability retained up to 100 kHz (against a 40 % loss above 10 kHz for permalloy), and a lower density (7.3 g/cm³ vs. 8.7 g/cm³), i.e. lighter devices. Its low remanence is decisive: it lets the magnetometer be read between actuation pulses with negligible contamination.

Table -3: Key Properties of the 1K107 FINEMET Nanocrystalline Core

Property	Value
Saturation flux density, B_{sat}	≈ 1.23 T
Relative permeability, μ_r (intrinsic)	1.0×10^5 to 1.5×10^5
Effective permeability, μ_{eff} (stacked core)	5.0×10^4 to 8.0×10^4
Coercivity, H_c	0.3 to 0.5 A/m
Remanent flux density, B_r	≈ 0.02 T
Frequency stability	Up to ~ 100 kHz
Permeability variation, -50°C to $+150^\circ\text{C}$	$< \pm 10$ %
Curie temperature	$\approx 570^\circ\text{C}$
Ribbon thickness	~ 20 – 30 μm

A design-decision model based on axiomatic design theory (functional requirements mapped to design parameters through a design matrix $[D] = [M][F]$) was used to fix the initial prototype: a FINEMET bar of 9.5×9.5×100 mm, a 5 V supply, a target dipole near 0.2 A·m², a solenoid length of 90 mm, and AWG-25 to AWG-33 wire, with the number of ribbon layers constrained between 1 and 15 to minimize mass. Among fabricated prototypes, the nanocrystalline cores showed the least hysteresis and the most linear actuation, with the best magnetization-to-mass ratio (4.959×10^{-3} for unit T0100-1).

4. MATHEMATICAL MODELING AND DESIGN CALCULATIONS

4.1 Magnetic Circuit and Effective Permeability

Treating the rod as a magnetic circuit, the coil magnetomotive force $F = N I$ drives flux through the core reluctance $\mathcal{R} = l/(\mu_0 \mu_r A)$, giving a core flux density that rises linearly with current until saturation. For a slender rod the demagnetizing factor N_d limits the usable permeability:

$$\mu_{\text{eff}} = \mu_r / [1 + N_d (\mu_r - 1)] \quad (3)$$

Because N_d for a high-aspect-ratio cylinder is of order 10^{-3} or lower, a high-permeability nanocrystalline core retains a large fraction of its intrinsic permeability, whereas a cube-like body ($N_d \approx 1/3$) gains almost nothing from the core. For a well-stacked 1K107 core, $\mu_{\text{eff}} \approx 50,000$ –80,000 is realistic.

4.2 Dipole Moment and Torque – 3U Design Example

For a target $m = 0.20$ A·m² at $I = 1$ A, using a 1K107 core of 95×10×10 mm formed from ten stacked 20 mm×0.025 mm ribbons and a conservative μ_{eff} , Eq. (1) gives approximately 800 turns. In LEO (400–600 km) the geomagnetic field is 30–60 μT ; taking a design value $B = 40$ μT , Eq. (2) gives a peak torque

$$|\tau_{\text{max}}| = (0.20)(40 \times 10^{-6}) \approx 8 \mu\text{N} \cdot \text{m} \quad (4)$$

This exceeds the gravity-gradient, aerodynamic and solar-radiation-pressure disturbance torques on a 3U bus by roughly a factor of five to ten, giving adequate control-authority margin.

4.3 Coil, Electrical and Thermal Design

AWG-28 copper wire (bare 0.321 mm, insulated 0.361 mm, 0.080 mm², 0.212 Ω/m at 20 $^\circ\text{C}$) is selected. With a winding efficiency $\eta \approx 0.83$ for round wire in a rectangular window, 800 turns are realized as four layers of 200 turns. The resulting coil inductance is $L \approx 33.5$ mH; at a 20 kHz PWM frequency inductive reactance dominates, which sets the driver design. The DC ohmic loss $P = I^2 R$ must be

dissipated radiatively in vacuum (emissivity $\epsilon \approx 0.9$, Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$), keeping the coil below its temperature limit. Table -4 summarizes the design point.

Table -4: Summary of the 3U Magnetorquer Design Point

Quantity	Value
Core material / size	1K107 FINEMET, 95×10×10 mm (stacked ribbon)
Target dipole moment	0.20 A·m ² at 1 A
Turns / layers	~800 turns, 4 layers × 200 turns
Wire	AWG-28 copper, 0.212 Ω/m
Coil inductance, L	≈ 33.5 mH
Peak torque (40 μT)	≈ 8 μN·m
PWM frequency	20 kHz

5. CONTROL ARCHITECTURE

Fig -2 gives the operational logic of the 3U ADCS, from ejection out of the Poly-Picosatellite Orbital Deployer (P-POD) through initialization, state measurement, attitude estimation, mode selection and closed-loop control until stable mission pointing. The two control branches B-dot detumbling and three-axis stabilization share a common dynamics-update and sensor-feedback loop.

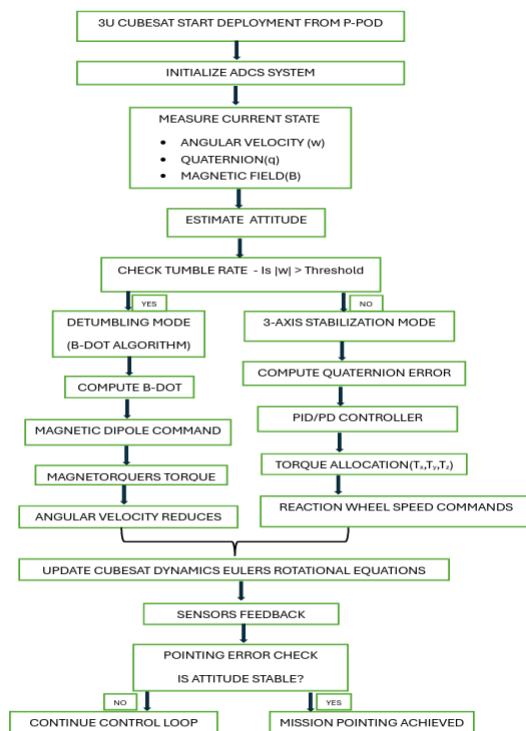


Fig -2: Overall control flow of the 3U CubeSat ADCS, showing the detumbling and three-axis stabilization branches and the common feedback loop.

5.1 Detumbling: The B-dot Law

After deployment the satellite tumbles at typically 5–20 °/s. Using only the magnetometer and the rods, the rate of change of the body-frame field is computed numerically,

$$\dot{B} \approx [B(k) - B(k-1)] / \Delta t \approx -\omega \times B \quad (5)$$

and the commanded dipole is made proportional to its negative, $m = -k \dot{B}$, clipped to the maximum dipole of the rod. The resulting torque always opposes the rotation, so the rotational kinetic energy decreases monotonically and the body rate decays. For a 3U bus starting near 10 °/s, convergence below 1 °/s is normally reached within two to five orbits.

5.2 Three-Axis Stabilization and Momentum Management

Once the rate falls below threshold, the estimated quaternion q is compared with the commanded q_d to form the error $q_e = q_d^{-1} \otimes q$. A proportional-derivative law

$$T_c = -K_p q_{ev} - K_d \omega \quad (6)$$

Drives the attitude error to zero with a damping ratio near 0.7. Reaction wheels supply the fast component of the commanded torque; the magnetorquers supply the slowly varying component and, crucially, desaturate the wheels. Both branches converge on Euler's rotational equations,

$$J \dot{\omega} + \omega \times (J\omega + h_w) = \tau_{ctrl} + \tau_{dist} \quad (7)$$

integrated together with the quaternion kinematics $\dot{q} = \frac{1}{2} \Omega(\omega)q$. The rod designed here appears in four blocks of Fig -2 detumbling torque generation, dipole command, torque allocation and wheel momentum management confirming its central role in the architecture.

6. SIMULATION RESULTS AND DISCUSSION

6.1 Model and Parameters

The coupled rigid-body and magnetic equations were integrated for a tumbling 3U CubeSat detumbled by the designed rod alone under the B-dot law. The geomagnetic field was evaluated along the orbit from a tilted-dipole model so that its rotation in the body frame is reproduced, and each commanded dipole component was clipped to the rod saturation limit. Table -5 lists the parameters.

Table -5: Parameters Used in the B-dot Detumbling Simulation

Parameter	Value
Spacecraft	3U CubeSat, 3.5 kg class
Principal inertias	$J_x = J_y \approx 0.035 \text{ kg}\cdot\text{m}^2$, $J_z \approx 0.006 \text{ kg}\cdot\text{m}^2$
Orbit	Circular LEO, 500 km, near-polar
Geomagnetic field	Tilted dipole, $\sim 30\text{--}50 \text{ }\mu\text{T}$
Control law	B-dot, $\mathbf{m} = -k \dot{\mathbf{B}}$
Max dipole per axis	$\pm 0.155 \text{ A}\cdot\text{m}^2$ (rod + driver saturation)
Actuators	Three orthogonal rods (one per axis)
Initial rates	$\omega_x \approx +4.8$, $\omega_y \approx -3.0$, $\omega_z \approx +5.0 \text{ }^\circ/\text{s}$
Initial rate magnitude	$ \omega _0 \approx 7.5 \text{ }^\circ/\text{s}$
Duration	6000 s ($\approx$ one orbit)

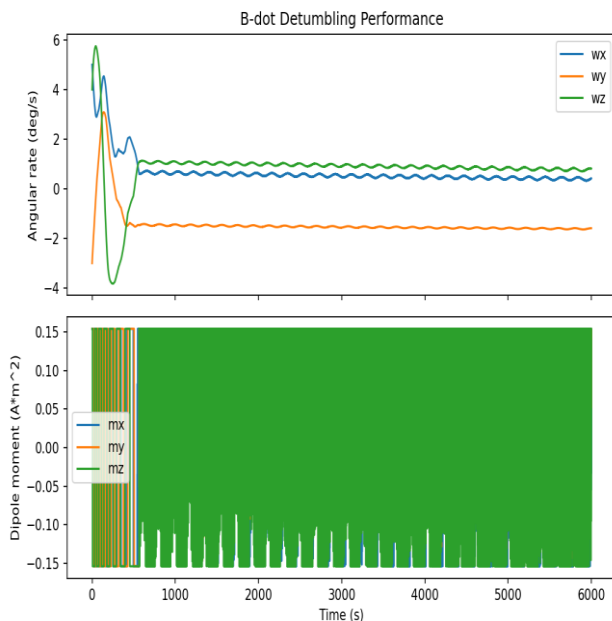


Fig -3: B-dot detumbling of the 3U CubeSat: (top) body angular-rate components; (bottom) commanded magnetic dipole moment showing saturated bang-bang operation at $\pm 0.155 \text{ A}\cdot\text{m}^2$.

6.2 Angular-Rate Response

Three phases are visible in the upper plot of Fig -3. During the first ~ 250 s the individual components do not decrease monotonically ω_z briefly rises before reversing because the gyroscopic coupling $\omega \times (J\omega)$ redistributes

momentum in an asymmetric body and because magnetic control is under-actuated (no torque about the instantaneous field direction). The physically meaningful quantity, the total rotational kinetic energy, nonetheless decreases from the first cycle. Between about 250 and 600 s all components converge rapidly; by ~ 600 s the rate magnitude has fallen from $7.5 \text{ }^\circ/\text{s}$ to about $2.0 \text{ }^\circ/\text{s}$, a reduction near 76 % within ten minutes. Beyond 600 s the decay becomes slow, with a small orbital ripple superimposed as the field vector rotates in the body frame. The residual magnitude of about $1.8 \text{ }^\circ/\text{s}$ at 6000 s is the component of momentum that has aligned with the local field, whose removal depends on the slow rotation of the field over successive orbits; this is the well-known behavior of magnetic-only control, not a shortfall of the actuator.

6.3 Dipole Response and Design Implications

The lower plot shows the commanded dipole switching between the $\pm 0.155 \text{ A}\cdot\text{m}^2$ saturation limits a bang-bang regime that produces the maximum available detumbling torque and hence the shortest detumbling time. It is, however, the worst case electrically: the coil carries rated current almost continuously, so the ohmic dissipation of Section 4 must be sustained rather than intermittent, and the driver, battery and coil thermal path must be sized for continuous rated operation over several orbits. That the command never exceeds $0.155 \text{ A}\cdot\text{m}^2$ also confirms the core stays well below saturation, preserving its effective permeability and linearity. The continuous saturation indicates the B-dot gain is larger than strictly necessary; adding a dead-band or duty-cycle limit would move the actuator into proportional operation later in the maneuver, cutting average power and current reversals at the cost of a marginally longer detumbling time. Table -6 summarizes the performance.

Table -6: Summary of the B-dot Detumbling Performance

Metric	Result
Initial rate magnitude $ \omega _0$	$\approx 7.5 \text{ }^\circ/\text{s}$
Rate magnitude at 600 s	$\approx 2.0 \text{ }^\circ/\text{s}$
Rate magnitude at 6000 s	$\approx 1.8 \text{ }^\circ/\text{s}$
Overall reduction	$\approx 76 \%$
Time to remove bulk of tumble	$\approx 550\text{--}600 \text{ s}$ ($< 10 \text{ min}$)
Residual components at 6000 s	$\omega_x \approx +0.4$, $\omega_y \approx -1.6$, $\omega_z \approx +0.8 \text{ }^\circ/\text{s}$
Peak commanded dipole	$0.155 \text{ A}\cdot\text{m}^2$ (saturation)
Actuator duty	Continuous saturated (bang-bang)
Time to reach $1 \text{ }^\circ/\text{s}$ (extrapolated)	2–5 orbits

6.4 Validation

Taken with the earlier design steps, the simulation validates the actuator on four counts. The dipole of the designed rod is sufficient to recover from a $7.5^\circ/\text{s}$ tumble without a larger actuator; the torque exceeds the environmental disturbances by close to an order of magnitude; the core stays in its linear region throughout, so the low coercivity and remanence of the nanocrystalline material are retained and the magnetometer can be read between pulses; and the simulation defines the electrical envelope continuous rated current with frequent polarity reversals against which the driver and thermal design must be qualified. Independently, axisymmetric finite-element analysis reproduced the analytical dipole within 2–5 %, and Helmholtz-coil measurements on a prototype gave $0.177\text{--}0.181\text{ A}\cdot\text{m}^2$ at $\pm 0.5\text{ A}$, a torque of $6.9\text{--}7.2\text{ }\mu\text{N}\cdot\text{m}$ in a $40\text{ }\mu\text{T}$ field, and coil parameters $L \approx 32.9\text{ mH}$ and $R \approx 4.62\text{ }\Omega$, all close to prediction. Analysis, simulation and measurement therefore form a consistent chain of evidence.

7. CONCLUSION AND FUTURE WORK

A magnetorquer rod for the ADCS of a 3U CubeSat was designed, modeled and simulated using a 1K107 FINEMET nanocrystalline core. Analytical magnetic-circuit and coil models produced a rod delivering about $0.20\text{ A}\cdot\text{m}^2$ from roughly 800 turns of AWG-28 wire, with a peak torque near $8\text{ }\mu\text{N}\cdot\text{m}$ that exceeds 3U disturbance torques by five to ten times. Finite-element analysis matched the analytical dipole within 2–5 %, and prototype measurements ($0.177\text{--}0.181\text{ A}\cdot\text{m}^2$; $L \approx 32.9\text{ mH}$; $R \approx 4.62\text{ }\Omega$) confirmed the design. In closed-loop simulation the rod, acting alone under the B-dot law, removed about 76 % of a worst-case $7.5^\circ/\text{s}$ tumble most of it within ten minutes while staying within its $\pm 0.155\text{ A}\cdot\text{m}^2$ saturation limit and its linear magnetic region. The nanocrystalline core's near-linear response and low remanence gave a 35–50 % improvement in linearity, hysteresis and mass efficiency over permalloy and simplified both the hardware and the control software.

Two limitations frame the future work: the continuous saturated operation of the coil is the design-driving electrical and thermal condition, and the slow terminal convergence is inherent to magnetic-only control. Both point to B-dot gain tuning, multi-orbit simulation and handover to the reaction-wheel stabilization branch, in which the rod provides momentum management. A slender cylindrical core is favored because its low demagnetizing factor ($N_d \sim 10^{-3}$) preserves effective permeability, its axisymmetry allows accurate 2-D modeling and clean alignment, and its solenoidal winding gives the lowest resistance and a uniform thermal path. Further work will optimize the length-to-diameter ratio, investigate stepped/tapered and ribbon-wound cores to suppress eddy currents during rapid reversals, and integrate the driver electronics, current sensing and thermal interface

into a single flight-qualified unit, moving the design from a validated laboratory actuator toward in-orbit demonstration.

REFERENCES

- [1] A. Poghosyan and A. Golkar, "CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions," *Progress in Aerospace Sciences*, vol. 88, pp. 59–83, 2017.
- [2] J. R. Wertz (Ed.), *Spacecraft Attitude Determination and Control*, vol. 73. Springer Science & Business Media, 2012.
- [3] S. W. Janson and T. Mason, "CubeSat standardization: Current status and perspective," *AIAA SPACE Conference*, 5372, 2013.
- [4] M. J. Sidi, *Spacecraft Dynamics and Control: A Practical Engineering Approach*, vol. 7. Cambridge University Press, 1997.
- [5] P. C. Hughes, *Spacecraft Attitude Dynamics*. Courier Corporation, 2012.
- [6] J. R. Wertz and W. J. Larson (Eds.), *Space Mission Analysis and Design*, no. 8. Microcosm Press, 1999.
- [7] M. L. Psiaki, "Magnetic torquer attitude control via asymptotic periodic linear quadratic regulation," *Journal of Guidance, Control, and Dynamics*, vol. 24, no. 2, pp. 386–394, 2001.
- [8] G. Herzer, "Nanocrystalline soft magnetic alloys," *Handbook of Magnetic Materials*, vol. 10, pp. 415–462, 1997.
- [9] E. Silani and M. Lovera, "Magnetic spacecraft attitude control: a survey and some new results," *Control Engineering Practice*, vol. 13, no. 3, pp. 357–371, 2005.
- [10] M. Lovera, E. De Marchi, and S. Bittanti, "Periodic attitude control techniques for small satellites with magnetic actuators," *IEEE Transactions on Control Systems Technology*, vol. 10, no. 1, pp. 90–95, 2002.
- [11] O. Brown and P. Eremenko, "The value proposition for fractionated space architectures," *AIAA Space Conference and Exposition*, 2006.
- [12] H. K. Kuga, V. Carrara, and K. R. Rao, "Attitude determination with magnetometer and earth sensors," *Mathematical Problems in Engineering*, vol. 7, no. 5, pp. 373–381, 2001.
- [13] V. Carrara and H. K. Kuga, "A systematic approach for the design of a CubeSat attitude control system," 2007.

- [14] K. D. Kumar, "Satellite attitude control using three magnetorquers," *Aerospace Science and Technology*, vol. 12, no. 3, pp. 284–294, 2008.
- [15] T. Soares, A. Costa, and L. C. Goes, "Magnetorquer design comparison using FINEMET and FeNi50 core materials," *IEEE Transactions on Magnetics*, vol. 59, no. 3, pp. 1–8, 2023.
- [16] S. W. Kim and J. L. Junkins, *Introduction to Dynamics and Control of Flexible Structures*. AIAA, 2001.
- [17] Y. Yoshimura, "Nanocrystalline soft magnetic materials and their applications," *Journal of Magnetism and Magnetic Materials*, vol. 272, pp. 1558–1565, 2004.
- [18] Hitachi Metals, *FINEMET Nanocrystalline Soft Magnetic Material – Technical Data*, Product Catalog, 2016.
- [19] T. W. Flatley and D. A. Henretty, "A B-dot acquisition controller for the RADARSAT spacecraft," *Flight Mechanics Symposium Proceedings*, pp. 20–22, 1996.
- [20] D. Meeker, *Finite Element Method Magnetics (FEMM) User's Manual*, Version 4.2, 2010. [Online]. Available: <http://www.femm.info/wiki/Documentation>
- [21] B. Risi, L. Riggi, and R. Mugnuolo, "Passive magnetic attitude control system for the UNISAT-4 microsatellite," *Acta Astronautica*, vol. 61, no. 10, pp. 885–893, 2007.
- [22] J. Bouwmeester and J. Guo, "Survey of worldwide pico- and nanosatellite missions, distributions and subsystem technology," *Acta Astronautica*, vol. 67, no. 7–8, pp. 854–862, 2010.
- [23] J. C. Springmann, J. W. Cutler, and H. Bahcivan, "Magnetic sensor calibration and residual dipole characterization for application to nanosatellites," *AIAA Guidance, Navigation, and Control Conference*, 4550, 2012.
- [24] M. Wood and W. H. Chen, "Attitude control of magnetically actuated satellites with an uneven inertia distribution," *Aerospace Science and Technology*, vol. 25, no. 1, pp. 29–39, 2013.
- [25] M. Y. Ovchinnikov, V. I. Penkov, D. S. Roldugin, and A. V. Pichuzhkina, "Three-axis attitude determination and control system for small satellites," *Acta Astronautica*, vol. 121, pp. 75–83, 2016.
- [26] W. H. Steyn, "Comparison of low-earth-orbit satellite attitude controllers submitted to controllability constraints," *Journal of Guidance, Control, and Dynamics*, vol. 21, no. 3, pp. 441–448, 1998.
- [27] R. Wisniewski and F. L. Markley, "Optimal magnetic attitude control," *Proc. 14th AAS/AIAA Space Flight Mechanics Meeting*, pp. 1015–1034, 2014.
- [28] F. Celani, "Robust three-axis attitude stabilization for inertial pointing spacecraft using magnetorquers," *Aerospace Science and Technology*, vol. 42, pp. 393–407, 2015.
- [29] M. Romano and B. K. Agrawal, "Three-dimensional H_∞ attitude control of a large flexible space structure," *Journal of Guidance, Control, and Dynamics*, vol. 27, no. 1, pp. 97–106, 2004.
- [30] M. F. Mehrjardi, F. Sangtarash, and N. Sheikhy, "Design and manufacturing of a research magnetic torquer rod," *IEEE Aerospace and Electronic Systems Magazine*, vol. 31, no. 7, pp. 44–49, 2016.