Control Moment Gyroscopes – Pros and Cons

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***Abstract*—**Control Moment Gyroscopes (CMGs) are advanced devices for satellite attitude determination and control systems (ADCS), providing precise angular momentum management through gyroscopic torque. CMGs offer high torque efficiency, scalability, and continuous torque delivery, overcoming traditional reaction wheels' limitations. However, conventional CMGs face significant challenges, including singularity constraints, mechanical complexity, and low angular momentum density. Innovations like Tensor Tech's spherical motor CMG significantly mitigate these issues, offering enhanced performance across various satellite platforms.

I. Introduction

Satellite technology advancements drive increased demands for agile, responsive attitude control systems. Control Moment Gyroscopes (CMGs) emerge as superior alternatives to traditional reaction wheels by providing significant advantages in power efficiency, torque, and maneuverability. This paper explores CMGs' operational principles, advantages, traditional limitations, and innovative solutions by Tensor Tech.

II. Background and Theory

A. Scaling Analysis for Satellite ADCS Requirements

The attitude control requirements of satellites are intricately tied to their physical dimensions. A fundamental scaling analysis provides important insights into how torque and power demands evolve with increasing satellite size.

Consider a satellite approximated as a cube with side length d in Figure 1.

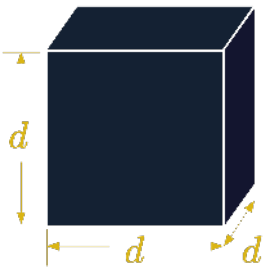


Fig. 1. Cubic satellite geometry illustrating dimension d used in scaling analysis for volume, surface area, and moment of inertia.

The volume of such a satellite scales with, representing the physical mass and internal capacity:

$$Volume \propto d^3 \quad (1)$$

The moment of inertia, which directly impacts the torque required for the same amount of rotational acceleration, scales with d^5. This stems from its dependence on both mass ($\propto d^3$) and the square of the radius of mass distribution ($\propto d^2$):

$$Moment\ of\ Inertia \propto d^5 \quad (2)$$

Simultaneously, the available power for a satellite typically scales with its solar panel area, which, under cube-like assumptions, scales with surface area $\propto d^2$:

$$Power\ Budget \propto Surface\ Area \propto d^2 \quad (3)$$

This contrast reveals a key design challenge: as satellite size increases, the power available for operating subsystems grows only quadratically, while the torque requirement for attitude control grows at a much steeper rate, proportional to d^5.

This scaling mismatch emphasizes the need for actuators that are not only capable of delivering higher torque, but can do so with higher torque-per-watt efficiency. The problem is more clearly seen when analyzing two critical requirements:

1) Maintaining the same angular acceleration for larger satellites

To achieve the same angular acceleration across satellite sizes, the required torque must match the increased inertia:

$$Required\ Torque \propto Moment\ of\ Inertia \propto d^5 \quad (4)$$

2) Maintaining the same slew rate

To maintain a consistent maximum slew rate across platforms, the control system must be able to store and exchange a corresponding amount of angular momentum:

$$Angular\ Momentum \propto d^5 \quad (5)$$

The angular momentum of actuators typically need to be traded by its volume. This reinforces the necessity for momentum-exchanging actuators (like CMGs or reaction wheels) with higher angular momentum density. Otherwise, the percentage of volume occupied by actuators within a satellite will grow larger and larger as satellites are getting bigger.

On the other hand, the power budget does not scale similarly. If a constant percentage of the satellite's available power is reserved for ADCS, the power allocated to

actuators increases only with d^2, meaning that there is less power per unit torque or per unit angular momentum as size increases.

Therefore, for larger satellites to maintain the same control authority (angular acceleration or slew rate), the chosen actuators must demonstrate:

- Higher torque-to-power ratio (Nm/W)
- Higher angular momentum density (Nms/kg or Nms/L)

These scaling laws highlight a fundamental reason why Control Moment Gyroscopes, which can generate high torque with minimal power input through gyroscopic action, are better suited than reaction wheels for larger satellites, remote sensing satellites which are seeking for better agility for better image revisit rate, as well as communication satellites which are seeking for more power budget for their payload [1]. CMGs offer a path to meeting d^5 scaling demands while consuming resources aligned closer to d^2 power availability.

III. Control Moment Gyroscope (CMG) Overview

A. Operating Principles

Variable-speed, Single-gimbal Control Moment Gyroscopes (SGCMGs) are angular momentum-exchanging devices that utilize a spinning rotor and a gimbal mechanism to generate torque in two orthogonal directions. Generally, all SGCMGs, whether they are variable-speed or not, consist of an internal rotor that spins at high speed around one axis, and a gimbal system that tilts the rotor around another axis. The combination of these motions allows the SGCMG to produce a torque vector that is the result of the cross product between the rotor's angular momentum and the gimbal angular velocity.

This gyroscopic torque τ_g is directed orthogonally to both the rotor spin axis and the gimbal tilt axis, enabling efficient torque production in a desired direction.

In addition, the torque τ_s can also be produced by speeding up or slowing down the rotor. This means a variable-speed CMG can output torque in two degrees of freedom: one via gyroscopic precession, and the other via direct reaction wheel-like acceleration.

$$\tau_z = I_z \dot{\omega}_z \quad (6)$$

$$\vec{\tau_z} \parallel \vec{\omega} \quad (7)$$

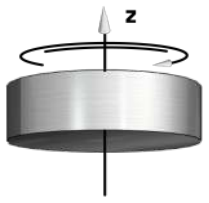


Fig. 2. The working principle of rotor spinning about $\hat{z}$ and torque is generated on such direction for reaction wheels

$$\tau_s = I_s \dot{\omega}_s \quad (8)$$

$$\tau_t = I_s \omega_g \omega_s \quad (9)$$

$$\tau_g = I_s \dot{\omega}_g \quad (10)$$

$$\vec{\tau} \perp \vec{\omega} \quad (11)$$

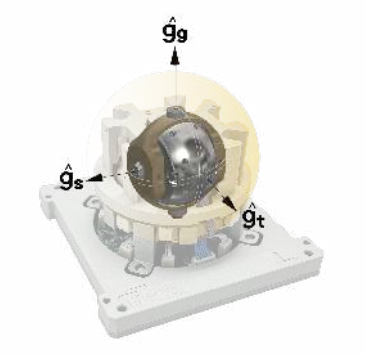


Fig. 3. The working principle of torque generation on $\hat{g}_s$, and $\hat{g}_t$ through gimbal motion on $\hat{g}_g$ axis in SGCMG.

B. Comparison with Reaction Wheels

Reaction wheels are single-axis momentum exchange devices that generate torque by varying the spin rate of a flywheel. The torque is proportional to the rotor's angular acceleration and is directed along the axis of rotation.

However, this direct drive mechanism has limitations. Since the generated torque is always aligned with the rotor's angular velocity vector, the power consumption scales with the torque output.

In contrast, CMGs can produce torque that is orthogonal to the rotor's angular velocity vector. As the torque vector is nearly orthogonal to the angular velocity vector, the mechanical power can be minimized for the same level of torque. This is a key efficiency advantage.

For instance, a reaction wheel delivering 1 Nms of angular momentum at peak torque can require up to 200W of electrical power. A similarly rated CMG, exploiting gyroscopic precession, may consume less than 20W while delivering equivalent or greater torque. This superior torque-to-power efficiency makes CMGs particularly attractive for missions requiring agile maneuvering or for spacecraft constrained by limited power budgets.

In summary, while reaction wheels operate on a linear input-output basis in a single axis, CMGs operate with higher degrees of freedom and more efficient energy usage, offering improved performance for modern ADCS architectures.

IV. Advantages of CMGs

A. Torque Efficiency and Power Consumption

One of the most compelling advantages of Control Moment Gyroscopes (CMGs) lies in their remarkable torque efficiency. Unlike reaction wheels, which generate torque by directly accelerating or decelerating a spinning mass along a fixed axis, CMGs generate torque gyroscopically — through the coordinated tilting of a spinning rotor. This mechanism allows torque to be produced orthogonally to the rotor's angular velocity vector, often resulting in a more efficient conversion of mechanical energy.

This distinction leads to a significant disparity in power consumption for equivalent torque output. Since the torque vector of the reaction wheel is aligned with the wheel's spin axis, the mechanical power term that comes from the dot product of torque vector and angular velocity vector will always contribute a great portion when the system is outputting high torque levels..

Conversely, the gyroscopic torque τ_g produced by a CMG can be orthogonal to the spin axis. Therefore, the

gimbal rotation rate and the constant angular momentum of the spinning rotor are nearly orthogonal. The torque can be generated with minimal additional energy, since the rotor speed remains relatively constant and energy is mainly spent on tilting.

This reduction in power usage becomes critically important in medium to large satellites, where power budgets are heavily taxed by other subsystems such as communication payloads, computing platforms, and propulsion systems. CMGs offer a way to maintain high agility without compromising other mission-critical operations.

B. Angular Momentum Density and Maneuverability

Another advantage of CMGs is their ability to generate and direct angular momentum with higher degrees of freedom, which directly translates to a wider angular momentum and an enhanced maneuverability. The angular momentum density of an actuator (typically measured in Nms per unit mass or volume) determines how fast it can speed up the slew rate of a satellite in a given physical space or mass budget.

Unlike reaction wheels, which are constrained to store angular momentum along their spin axis only, CMGs have the ability to steer the angular momentum vector through gimbal movement. This allows the actuator cluster to:

- Concentrate total angular momentum into a desired direction more quickly.
- Reconfigure the angular momentum vector dynamically during a maneuver.

In attitude control scenarios requiring fast and complex maneuvers — such as Earth observation with narrow pointing constraints or rapid retargeting in defense applications — this steering capability becomes a critical advantage.

Moreover, CMG clusters (e.g., four-CMG pyramid configurations) can achieve significantly larger angular momentum envelopes than a similarly sized cluster of reaction wheels. This envelope represents the set of all possible momentum vectors the system can produce, and CMGs enable broader coverage, as will be detailed in Section VII.

C. Power Efficiency Demonstrated in Repeated Slew Maneuvers

$$P_{Total} = P_{Mechanical} + P_{Iron} + P_{Copper} \quad (12)$$

$$P_{Mechanical} = P_{Friction} + P_{RotorManeuver} + P_{SatelliteManeuver} \quad (13)$$

$$P_{Maneuver} = \sum_{n=1}^{k} \vec{\tau_n} \cdot \omega_{\vec{R/I},n} \quad (14)$$

$$\omega_{\vec{R/I},n} = \omega_{\vec{R/S},n} + \omega_{\vec{S/I}} \quad (15)$$

$$\tau_{\vec{total}} = \sum_{n=1}^{k} \vec{\tau_n} \quad (16)$$

$$P_{Manuever} = \sum_{n=1}^{k} \vec{\tau_n} \cdot \omega_{\vec{R/S},n} + \sum_{n=1}^{k} \vec{\tau_n} \cdot \omega_{\vec{S/I},n} = \left(\sum_{n=1}^{k} \vec{\tau_n} \cdot \omega_{\vec{R/S},n}\right) + \tau_{\vec{total}} \cdot \omega_{\vec{S/I}} \quad (17)$$

R: Rotor Frame, S: Satellite Frame, I: Inertia Frame

In Equation 17, the $\left(\sum_{n=1}^{k} \vec{\tau_n} \cdot \omega_{\vec{R/S},n}\right)$ is the additional power consumed by the reaction wheels, compared to the CMGs.

To objectively compare the performance of attitude actuators in real-world scenarios, we analyze a common use case: a satellite executing repeated slew maneuvers back and forth along a single axis (e.g., from +X to –X). This type of maneuver is frequently used in Earth observation missions, target tracking, or coverage-based constellations that require rapid retargeting between fixed points.

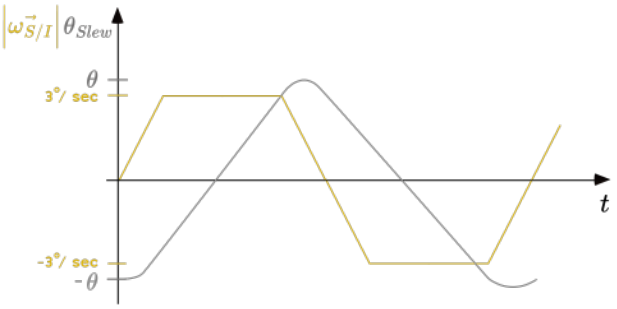


Fig. 4. Repeating single-axis slew maneuver profile used to evaluate actuator efficiency.

Assumptions:

– $MOI_{wheel} = 0.00015 \times MOI_{satellite}$

– 550 km Sun-synchronous orbit (SSO)

– 25% solar panel efficiency

– Satellite average density = 350 kg/m³

Figure 4 illustrates a time-history plot of such a repeating slew profile, with the following motion sequence:

- The satellite starts at a neutral orientation and accelerates toward a maximum positive slew rate (e.g., $+3^{\circ}/s$).
- After reaching this target speed, it holds the velocity briefly (coasting phase) before applying deceleration torque to stop at the maximum angle ($+\theta$).
- It then performs the same profile in reverse: accelerating toward -3°/s, holding speed, and braking at $-\theta$.
- This pattern continues periodically.

This maneuver requires alternating acceleration and deceleration torques, demanding that the actuator deliver peak torque within short time intervals. From a power standpoint, this dynamic profile is where CMGs show clear advantages.

Why CMGs Excel in This Scenario:

- Reaction wheels must vary rotor speed dramatically for each acceleration/deceleration phase, resulting in high electrical power demand, especially for larger satellites (see Section II).
- CMGs, by contrast, redirect their fixed angular momentum via gimbal actuation. Since the rotor spin rate is usually kept constant, less power is spent on rotor acceleration, and the torque output is achieved by relatively low-power gimbal motion.

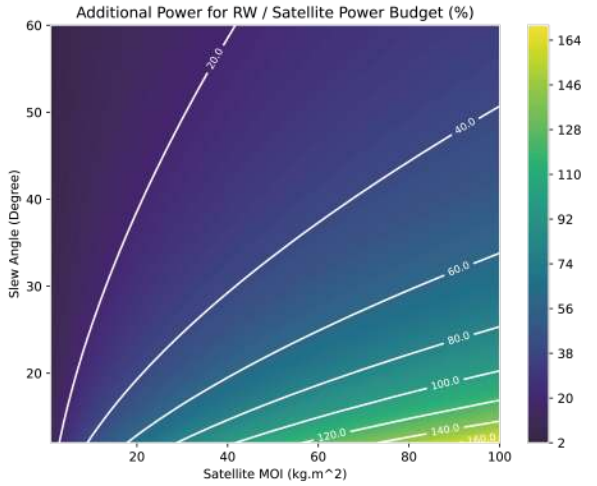


Fig. 5. Additional power for reaction wheels divided by the satellite power budget

V. Limitations and Challenges of Traditional CMGs

A. Mechanical Complexity

Traditional CMGs incorporate separate motors for rotor spin and gimbal maneuvers, introducing mechanical complexity, reliability concerns, and higher maintenance requirements. Increased complexity can lead to higher costs, over-sized mechanical parts, and susceptibility to mechanical failures.

B. Singularity Issues

Singularity, a significant operational limitation, occurs when CMG configurations restrict torque output directions, complicating control strategies. Sophisticated algorithms are essential to manage or circumvent singularity constraints, adding complexity to satellite operations. However, due to the variable-speed design of Tensor Tech's CMG that is based on Spheroical Motor technology. The additional degrees of freedom remove the need of doing singularity avoidance.

VI. Innovations in CMG Technology

A. Tensor Tech's CMG driven by the spherical motor

Traditional Control Moment Gyroscopes (CMGs) rely on two separate motors — one to spin the rotor and another to actuate the gimbal. This dual-motor configuration not only increases the system's complexity, mass, and size, but also requires electrical interfaces like slip rings to deliver power and control signals to the inner rotor, which rotates inside the gimbal.

To overcome these limitations, Tensor Tech developed a revolutionary spherical motor-based CMG, combining the rotor drive and gimbal actuation into a single integrated spherical motor. This innovation enables three-dimensional control of the rotor's orientation using a single electromagnetic structure, eliminating the need for separate axes of rotation and dramatically simplifying the design.



Fig. 6. TensorCMG driven by the spherical motor developed by Tensor Tech

Permanent magnets are mounted directly onto the rotor shell, and multi-axis control coils are embedded in the surrounding stator structure. Internally, the rotor contains strategically placed permanent magnets that interact with specially shaped coils embedded in the surrounding stator. These coils are driven with multi-phase current waveforms to generate a rotating magnetic field, controlling both the spin and the tilt of the rotor. This design transforms the CMG into a single-unit, all-magnetic drive system, with no mechanical linkages between motors and gimbals.

Because the entire unit is self-contained and symmetric, the CMG can maintain its spherical form factor regardless of the desired skew or tilt orientation. This eliminates one of the fundamental design compromises of traditional CMGs: skewing the gimbal to achieve full control authority increases the system's occupied volume. Tensor Tech's CMG avoids this entirely.

B. Comparison of CMGs with Traditional and Spherical Motor Technology

To better understand the benefit of Tensor Tech's innovation, let us consider the volume comparison between three types of actuators:

- Traditional Single-Gimbal CMG (SGCMG)
- Tensor Tech's SGCMG driven by the spherical motor technology
- Reaction wheel



Fig. 7. Volume comparison among Traditional SGCMG, Tensor Tech's CMG by spherical motor, and Reaction Wheel based on a single unit (volume ~ r^3)

As shown in Figure 7, for actuators designed to achieve the same angular momentum capacity. At first glance, the reaction wheel appears more compact, but this overlooks the spatial requirements when the actuators are deployed in full control clusters.

C. *Practical Volume and Reliability Advantages*

When four actuators are arranged in a pyramid configuration for three-axis control — a common practice in spacecraft ADCS systems — the total system volume diverges significantly across technologies, as visualized in Figure 8.

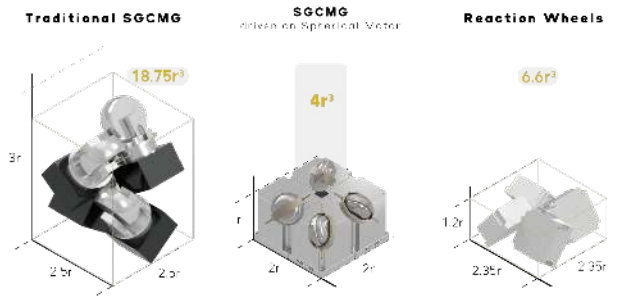


Fig. 8. Total system volume of a four-actuator pyramid cluster across technologies. CMGs based on the spherical motor offer the lowest system volume.

- A traditional SGCMG pyramid cluster can occupy more space due to the extra height and misaligned gimbals caused by skewing.
- CMGs based on the spherical motor maintain a volume, thanks to its shape-preserving tilt capability.
- A reaction wheel cluster, although smaller than the traditional CMG, still consumes more space than Tensor Tech's CMG cluster — and cannot offer the same torque-to-power advantages.

These dimensional comparisons reveal a key insight: Tensor Tech's CMG driven by the spherical motor technology not only shrinks individual unit size but also minimizes total system volume even after integration. This leads to critical benefits in:

- Mass and volume budget (especially for small satellites and larger)
- Mechanical integration complexity
- Thermal and electrical harnessing

D. *Reliability Redefined: A Slip Ring-Free Approach*

Further, Tensor Tech's CMG eliminates the use of slip rings, a known failure point in traditional CMG designs. By embedding the control coils externally and using electromagnetic coupling only, Tensor Tech's CMG driven by the spherical motor technology avoids issues related to wear, friction, or signal noise — making it inherently more reliable.

This architectural simplification also affects software. Since traditional CMGs often limit gimbal motion to avoid wear or overheating, control algorithms must constantly monitor angular limits and avoid singularities. Tensor Tech's CMG allows steering laws to focus primarily on power optimization and maneuver smoothness, rather than mechanical constraints — unlocking further performance and operational simplicity.

VII. Performance Analysis

A. *Angular Momentum Envelope Comparison*

To understand the operational effectiveness of different attitude actuators, we analyze the angular momentum envelope — the 3D space representing the total momentum vectors that an actuator cluster can achieve. This envelope is a vital metric for comparing maneuvering capacity and agility across control architectures.

Actuator clusters (reaction wheels or CMGs) are often configured in a pyramid geometry, where four devices are mounted with identical skew angles β relative to a spacecraft-fixed coordinate frame. The specific pyramid layout is illustrated in Figure 9. This geometry allows distributed control torque in three dimensions and forms the basis for the envelope analysis that follows.

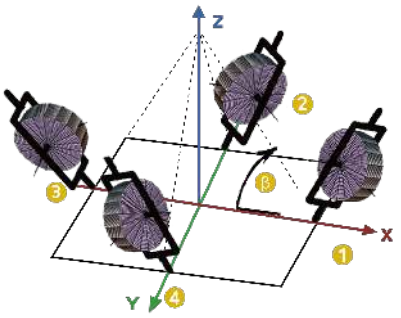


Fig. 9. Pyramid cluster configuration of four angular momentum actuators

1) Reaction Wheels in Pyramid Cluster

In a four-wheel pyramid configuration, each reaction wheel contributes angular momentum along its fixed spin axis. The resultant envelope, formed by vector summation of all wheel contributions, is bounded by the wheel spin axes and is therefore geometrically constrained.

Each reaction wheel contributes 1 Nms, and the maximum inscribed sphere radius in the envelope is ~1.5 Nms as shown in Figure 10. Despite using four actuators, the envelope remains geometrically limited due to fixed-axis storage. This results in a relatively flat and faceted envelope.

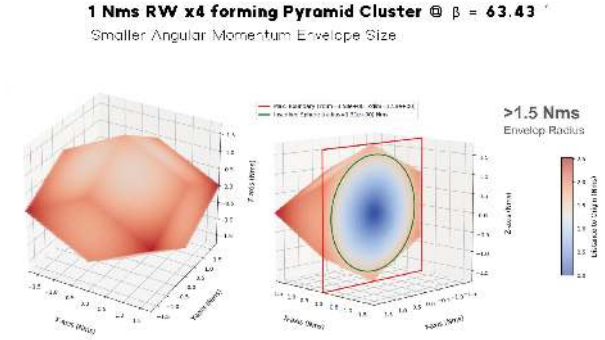


Fig. 10. Angular momentum envelope for four units of 1-Nms reaction wheels in a pyramid cluster, inscribed radius ~1.5 Nms.

2) Constant-Speed CMG (CSCMG) in Pyramid Cluster

In contrast, Control Moment Gyroscopes are inherently capable of steering their angular momentum vectors. When used in the same pyramid configuration, each CMG can tilt its gimbal axis to contribute in dynamically changing directions. This expands the boundary of the angular momentum envelope significantly.

For 1 Nms CSCMG, the resulting envelope has an inscribed sphere radius of ~2.8 Nms, as shown in Figure 11. The envelope is much rounder and volumetrically greater than the reaction wheel case. However, this comes with one major caveat: singularity. Constant-speed CMGs can face constraints in momentum vector direction due to their limited degrees of freedom — i.e., the angular momentum stored in the rotor's spin axis is typically fixed.

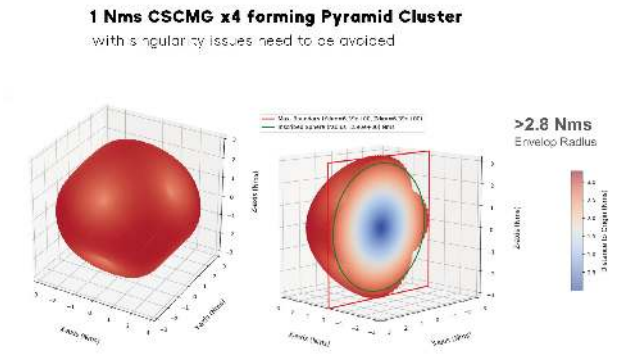


Fig. 11. Angular momentum envelope for four 1-Nms constant-speed CMGs (CSCMGs). Radius ≈ 2.8 Nms, but subject to singularity conditions.

3) Variable-Speed CMG (VSCMG) – Spherical Motor Based

Tensor Tech's variable-speed CMG (VSCMG) driven by a spherical motor eliminates these singularities while preserving the full steering capability [3]. Unlike CSCMGs, the spherical motor design enables continuous vector control without singularity limitations. As a result, the angular momentum envelope is as large as the CSCMG's (~2.8 Nms radius), but fully reachable in all directions.

The envelope, illustrated in Figure 12, retains the same high-performance characteristics but with better trajectory flexibility and algorithmic freedom — enabling full control authority in any direction without violating actuator constraints.

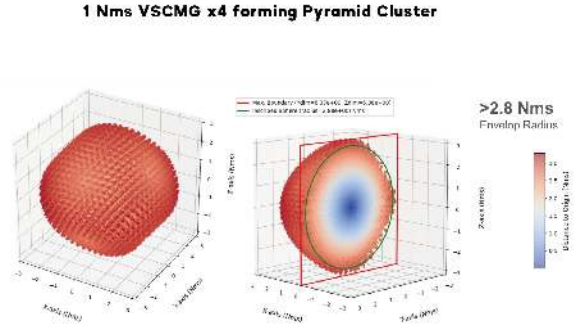


Fig. 12. Angular momentum envelope for 1-Nms spherical-motor VSCMG pyramid cluster. Singularity-free, fully reachable volume.

B. Redundancy and Singularity Advantages

Another major advantage of VSCMGs lies in their fault tolerance and graceful degradation. In typical ADCS designs, redundancy is critical — especially for missions requiring high reliability or extended lifespans. If two of four actuators in a pyramid configuration fail:

- A reaction wheel cluster would lose three-axis control
- A CSCMG cluster would lose full 3D control. The resulting envelope becomes invalid for certain orientations due to the inherent singularity surface [2]. This means some torque directions would become unachievable, risking mission failure.
- A VSCMG cluster, however, can continue to operate 3-axis torque control with only two working CMGs. The remaining CMGs adjust their spin rate and direction to reconstruct a reduced but valid 3D angular momentum envelope, ensuring continued control over all three axes — albeit at a reduced maximum slew rate.

This property is visualized schematically in degraded control simulations, where the VSCMG maintains a shrunk but spherical envelope in Figure 13, whereas CSCMGs collapse into a narrow band of motion in Figure 14.

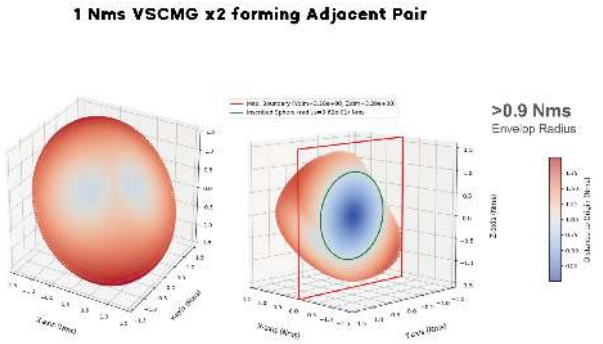


Fig. 13. Angular momentum envelope for four units of 1-Nms spherical-motor VSCMG in a pyramid cluster under two VSCMG failures, where the remaining pair operates as an adjacent configuration to maintain three-axis control with reduced envelope radius.

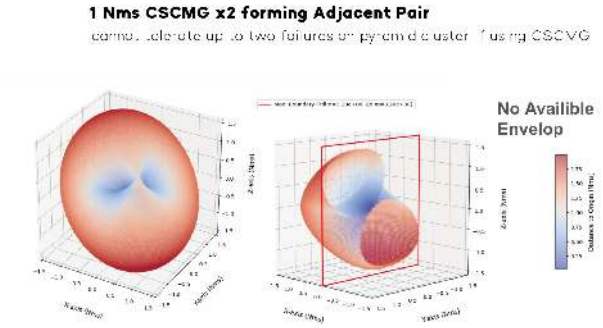


Fig. 14. Angular momentum envelope for four units of 1-Nms constant-speed CMGs (CSCMGs) in a pyramid cluster under two CSCMG failures.

The singularity-free characteristic of Tensor Tech's VSCMG not only provides higher nominal agility but also ensures robustness under failure. This makes it particularly attractive for constellation deployments, where autonomy and redundancy are key, and component reliability directly impacts long-term operational availability.

VIII. Conclusion

Control Moment Gyroscopes (CMGs) offer a powerful and efficient alternative to traditional reaction wheels for satellite attitude control, particularly in applications demanding high agility, low power consumption, and compact integration. Through detailed scaling analysis, this paper demonstrated that as satellite dimensions increase, torque and angular momentum requirements grow significantly faster than available power — highlighting the need for actuators with superior torque-to-power ratios.

Comparative studies of actuator architectures revealed that CMGs provide larger angular momentum envelopes and enhanced maneuverability through vector steering. Tensor Tech's innovation in spherical motor CMG technology further addresses the primary drawbacks of conventional CMGs — including size, complexity, and singularity limitations. By integrating spin and gimbal functions into a single spherical actuator, the design achieves:

- Dramatically reduced volume, both per unit and in cluster configuration.
- Elimination of mechanical slip rings, enhancing long-term reliability.

- Singularity-free control with robust fault tolerance and algorithmic flexibility.

Performance evaluations confirmed that Tensor Tech's variable-speed CMGs outperform traditional constant-speed CMGs and reaction wheel clusters in both nominal capability and redundancy scenarios [4]. The spherical motor CMG architecture not only enhances pointing performance but also enables mission designers to reduce satellite count by increasing individual satellite agility and revisit rate.

In conclusion, Tensor Tech's CMG driven by the spherical motor technology presents a leap forward in ADCS design, providing a compact, energy-efficient, and fault-tolerant solution that meets the demands of modern and future satellite missions across LEO, MEO, and GEO regimes.

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