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Attitude Determination and Control System with Variable-Speed Single-Gimbal Control Moment Gyroscopes for Nanosatellites

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ABSTRACT

This paper presents a novel Attitude Determination and Control System (ADCS) utilizing Variable-Speed Control Moment Gyroscopes (VSCMG) tailored explicitly for nanosatellites. The VSCMG was realized by spherical motor technology, in which a patented magnetic field design controls the inner rotor and gimbal. Because of the characteristics of the control moment gyroscope, the proposed ADCS offers improved attitude maneuverability and reduced power consumption, addressing the limitations of traditional ADCS solutions for nanosatellites. Furthermore, the adoption of spherical motor technology shrinks the VSCMG into a smaller form factor, which allows the VSCMG to be fitted into a nanosatellite. This research paper introduces the specifications of the integrated ADCS family based on VSCMG, as well as the components used in the system.

I. INTRODUCTION

Nanosatellites have emerged as a viable platform for various space missions due to their small size, lower costs, and rapid deployment capabilities. However, ensuring precise attitude determination and control poses a significant challenge for these satellites. Attitude Determination and Control System (ADCS) is crucial in achieving accurate pointing, stability, and maneuverability in space. To address the limitations of traditional ADCS solutions for nanosatellites, this study presents an ADCS with a Variable-Speed Control Moment Gyroscope (VSCMG).

Compared to Reaction Wheels (RWs) for satellite attitude control, utilizing control moment gyroscopes (CMGs) offers advantages. CMGs provide a higher torque-to-power ratio, allowing the satellite to maneuver with higher agility under the same consumed power. This increased torque capability enables rapid and agile attitude adjustments, essential for earth observation missions and satellites that need to save their power budget for the payload.

The VSCMG represents a hybrid actuator that combines the features of RWs and CMGs [1]. Unlike conventional CMGs, the VSCMG offers an additional degree of control, eliminating the common singularity issue. Furthermore, the VSCMG ensures continuous production of the desired torque, enhancing attitude control performance [2].

ADCS often employs a combination of different actuators to cater to diverse on-orbit operations. RWs are commonly used alongside magnetic control, where magnetorquers (MTQs) aid in unloading RW momentum and detumbling the spacecraft. The RWs then facilitate precise and rapid three-axis attitude control. While efforts have been dedicated to developing control laws and exploring the application of VSCMGs, their practical adoption for attitude control remains infrequent. RWs remain popular among small and nanosatellites, while CMGs remain the prevailing choice for larger satellites.

In this study, the author delves into the unique capabilities of the VSCMG, addressing its potential as an innovative actuator for the nanosatellite community. By minimizing the VSCMG with spherical motor technology, the VSCMG offers better agility with lower volume occupied compared to the RW-based ADCSs. Through years of research and development, Tensor Tech established the VSCMG as a viable alternative to traditional actuator systems. By adopting such technology, the saving volume and power for the spacecraft allow the user to focus on their payload and value-added services.

II. PERFORMANCE OF THE ADCS WITH CMG

The current ADCS is designed for nano and microsatellite applications. The four successfully developed configurations will be described in the following section. 3rd-party actuators like thrusters and sensors like star trackers can be integrated into the ADCS with configurable interfaces.

ADCS-10m

ADCS-10m is a highly self-contained configuration designed for 3 to 6U nanosatellites with one tuna-can, which utilizes one VSCMG for attitude control. The compact design allows for easy integration and improved volume utilization, requiring only 0.2U of volume within the satellite structure and one tuna-can for the VSCMG. Figure 1 presents the photograph of the ADCS-10m, while Table 1 shows its specifications.

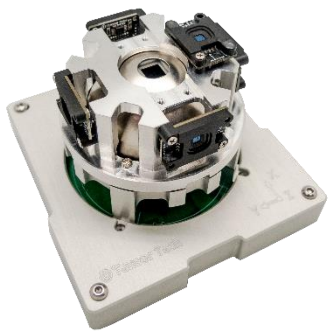

Figure 1: Photograph of the ADCS-10m module.

Table 1 The specification of the ADCS-10m

Parameter	Description	Typ.	Max.	Unit
Mass	Total mass		450	grams
Length	Including CMG, MCB, and MTQ	91.7		mm
Width		86.0		mm
Height		51.4		mm
Volume	Installed within the satellite structure		0.5	U
	Installed at tuna-can		0.2	
Pointing accuracy		1		deg
Current	5V bus	0.25	0.8	A
	3.3V bus	0.3	0.6	
	5V bus inrush current in 100 µs	0.04	0.1	
	3.3V bus inrush current in 400 µs	0.4	1	
Angular momentum storage			10	mNms
Torque	Output torque		1	mNm^2
Slew rate	3U or smaller		10	deg/s
	6U		5	deg/s
Magnetic dipole moment	Generate by MTQ on the x/y-axis		0.2	Am^2
	Generate by MTQ on the z-axis		0.1	

ADCS-20m

ADCS-20m is an optimized configuration designed for 6 to 12U nanosatellites with two tuna-cans using two VSCMG as a modified scissored-pair configuration. This configuration offers higher angular momentum storage capability compared to ADCS-10m. In addition to the volume utilized inside tuna-cans, it requires the installation of a main control board, three MTQ rods, and sun sensors. Table 2 presents the specifications of the ADCS-20m module.

Table 2 The specification of the ADCS-20m

Parameter	Description	Typ.	Max.	Unit
Volume	Installed within the satellite structure		1	U
	Installed at tuna-can		0.4	
Pointing accuracy		1		deg
Current	5V bus	0.3	1.2	A
	3.3V bus	0.45	0.9	
	5V bus inrush current in 100 µs	0.06	0.15	
	3.3V bus inrush current in 400 µs	0.6	1.5	
Angular momentum storage			20	mNms
Torque	Output torque		2	mNm^2
Slew rate	6U		5	deg/s
	12U		3	deg/s
Magnetic dipole moment	Generate by MTQ on the x/y/z-axis		0.8	Am^2

ADCS-40m

ADCS-40m employs four VSCMG to maximize the momentum storage and output torque, which presents a modified pyramid cluster CMG configuration. This configuration is suitable for 12U nanosatellites or larger microsatellites. It is worth noting that the ADCS-10m, ADCS-20m, and ADCS-40m modules can either be installed at the deployer's tuna-can, providing better volume utilization for most nanosatellites, or within the satellite structure depending on the mission requirement. Figure 2 presents the ADCS-10m installed at tuna-can, i.e., Installation Plan 1, and within the structure, i.e., Installation Plan 2.

ADCS-MTQ

Despite not using VSCMGs for attitude control, it is worth noting that the main control board of ADCS is capable of solely driving the MTQs to present an MTQ-based ADCS, which is a minimal configuration for less than 3U nanosatellite that requires sun-pointing and de-tumbling capabilities as shown in Figure 3.

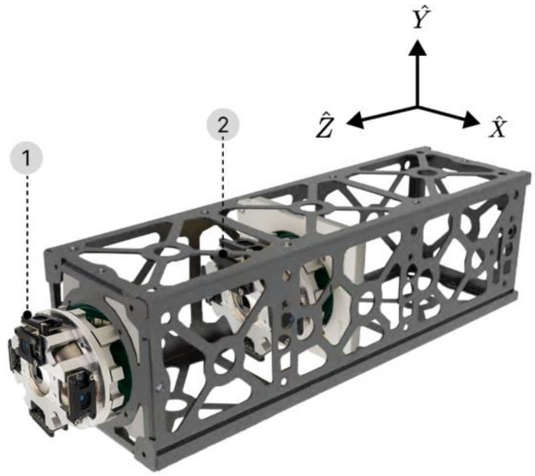

Figure 2: Installation Plans 1 and 2 for the ADCS-10m module.

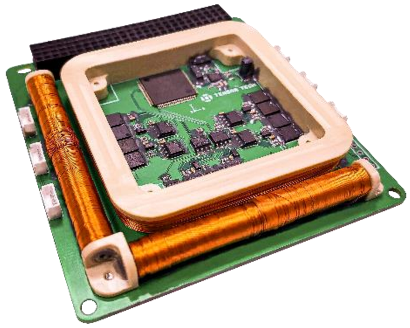

Figure 3: Photograph of the ADCS-MTQ module.

III. MAIN CONTROL BOARD

The Main Control Board (MCB) for ADCS is the primary control computer designed for attitude estimation, control, and communication. It is a flexible board compatible with the self-developed module and other commercial-off-the-shelf components, providing a simple register-based interface. On orbit, the On-Board Computer (OBC) only needs to switch modes to fulfill its mission, making the MCB a robust offload engine.

The MCB integrates an Inertial Measurement Unit (IMU) for rate measurement and a triaxial magnetometer for magnetic field measurement. The attitude control algorithms are also integrated into the MCB for all ADCS modules. Specifically, tumbling handling, steering control, EKF-based estimation, CMG controller, fault detection, and fault handling. Meanwhile, the MCB is designed to be compatible with GNSS receiver modules. In this case, the OBC can request the current position and time information from the MCB. The position and time data are essential to execute advanced mode operations, such as fine pointing, nadir pointing, and target tracking modes.

IV. CONTROL MOMENT GYROSCOPE

In the ADCS presented in this paper, the VSCMGs serve as the primary attitude actuator for precise pointing with higher slew rates. The VSCMG design offers improved satellite ADCS performance in terms of weight, volume, and power consumption. Static and dynamic unbalance calibration of the VSCMG rotor adheres to ISO1940 G0.4 standards. Figure 4 shows the gimbal, inner rotor, and the definition of the gimbal frame.

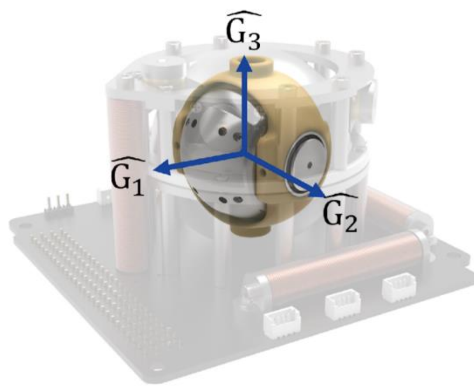

Figure 4: The definition of the gimbal frame.

The simplified torque output formulas for the x, y, and z axis can be defined by τ_x, τ_y, and τ_z, respectively in Equations (1) to (3):

$$\tau_x = I_y \omega_y \omega_x, \quad (1)$$

$$\tau_y = I_y \dot{\omega}_y, \quad (2)$$

$$\tau_z = I_z \dot{\omega}_z, \quad (3)$$

where I denotes the moment of inertia of the rotor, ω denotes the angular velocity, and $\dot{\omega}$ denotes the angular acceleration. In Figure 4, The $\widehat{G_1}$, $\widehat{G_2}$, and $\widehat{G_3}$ axes are attached to the motor gimbal (the brown component) and controlled to spin in the $\widehat{G_3}$-direction. The $\widehat{G_3}$-axis is the tilting axis; the $\widehat{G_2}$-axis is referred to as the inner rotor rotational axis, and the speed upon $\widehat{G_2}$-axis is the inner rotor speed. Figure 5 shows the photograph of the VSCMG.

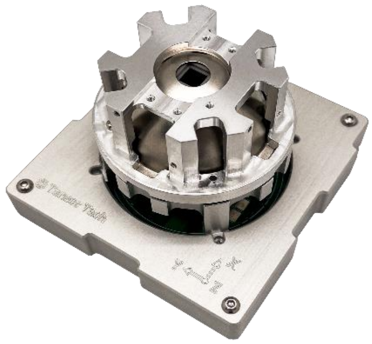

Figure 5: The photograph of the VSCMG.

V. MAGNETORQUER

Triaxial Magnetorquers (MTQs) can provide de-tumbling, de-saturation, and CMG failure backups. The self-developed MTQ consists of a high linearity and low hysteresis magnetic core wrapped with a wire coil, through which an electric current is passed. When a current is applied, a magnetic dipole moment is created, which interacts with the geomagnetic field. The resulting torque enables the satellite to rotate around one or more of its axes.

VI. FINE SUN SENSOR

Fine sun sensors are required to determine the sun vector. FSS-15 is a minimized fine sun sensor that features a microcontroller to produce a pre-calibrated error table for a tabulated correction, which enables it to achieve a higher precision. Figure 6 presents the FSS-15 fine sun sensor photograph with a central quadrant photodiode. Moreover, since the magnetic leakage from the attitude actuators such as RWs and CMGs often affect the magnetometers, a fine sun sensor with a triaxial magnetometer is also developed, called FSS-15M, as shown in Figure 7.

When mounting the fine sun sensors on the satellite structure or solar panel, the user can ensure a sufficient distance between the magnetometer and the attitude actuators, thereby securing the reliability of the data measured by the magnetometer. Refer to Figure 2; installing one FSS-15M fine sun sensor on the opposite side of the tuna-can in Installation Plan 1 is required since the five FSS-15 will be mounted on the frame of the VSCMG. Meanwhile, ensuring that the selected locations for fine sun sensors provide a sufficient Field of View (FOV) is crucial when using Installation Plan 2.

Figure 6: The photograph of the FSS-15 fine sun sensor.

Figure 7: The FSS-15M fine sun sensor photograph with a triaxial magnetorquer.

VII. CONCLUSION

The Variable-Speed Control Moment Gyroscope (VSCMG) presents a promising hybrid actuator solution for spacecraft attitude control. Combining the features of reaction wheels (RWs) and Control Moment Gyroscopes (CMGs) and minimizing them with spherical motor technology, the VSCMG offers enhanced control flexibility, improved performance, and reduced singularity concerns.

Moreover, the complete ADCS product family offers the attitude sensors and the embedded control firmware, allowing the user to adopt the VSCMG technology easily without the need to develop their own control algorithms.

References

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2. J. Liao, T. Yen, S. Lee, A. Chang, L. Hou, J. H. Hsieh, “Single-Gimbal Control Moment Gyro with Spherical Motor Technology for Attitude Determination and Control System,” in 73rd Int. Astronautical Congr., 2022. IAC-22-B4.6B.5.