Practical Results on the Development of a Control Moment Gyro based Attitude Control System for Agile Small Satellites

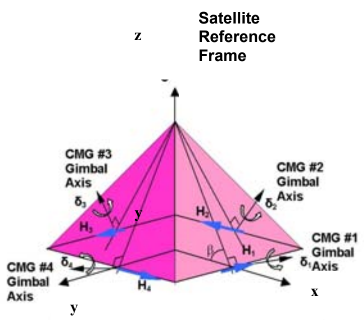
V.J. Lappas[1], WH Steyn[2], C.I. Underwood[1]

[1]Surrey Space Centre, University of Surrey, Guildford, Surrey GU2 5XH, UK

[2]University of Stellenbosch, Stellenbosch , 7602, South Africa

Abstract: In this paper a new practical Attitude Control System is proposed, based on Control Moment Gyroscopes (CMG). These actuators can provide unique torque, angular momentum and slew rate capabilities to small satellites without any increase in power, mass or volume. This will help small satellites become more agile and maneuverable. Agility considerably increases the operational envelope and efficiency of spacecraft and substantially increases the return of earth and science mission data. The paper focuses on the practical work on developing the hardware for a low cost, miniature CMG for agile small satellites. Experimental results indicate the potential benefits of using CMGs. Specifically, a cluster of four Single Gimbal CMGs (SGCMG) is used to practically demonstrate full 3-axis control for a microsatellite class spacecraft. Additionally, results are presented on the development of a larger SGCMG proposed as an experimental payload for future enhanced microsatellite missions.

Introduction: A Single Gimbal CMG (SGCMG) is a CMG with a constant speed momentum wheel, gimbaled in one axis only. For full three-axis control of a spacecraft, a cluster of four CMGs is normally used. CMGs, due to their inherit gyroscopic properties can potentially generate large torque and angular momentum outputs, in a more efficient way than current technologies such as reaction or momentum wheels. Depending on the gimbal axes a CMG can be distinguished to a Single Gimbal CMG (SGCMG) and Double Gimbal CMG (DGCMG). The type and number of CMGs that can be used in an ACS is a trade off between performance, cost, mechanical and algorithm complexity. SGCMGs and Variable Speed CMGs (VSCMG) are the most powerful (from the torque point of view) of all, but SGCMGs require a minimum of four units for full 3-axis control in order to avoid singularities. SGCMGs have been thoroughly studied in the past[1-11] and have been baselined to be used in future space missions[1-3,16,18]. The most significant drawback with SGCMGs is the problem of singularities. This is the condition in which no torque can be produced for certain sets of gimbal angles. When the gimbal angles encounter singularities they 'lock-up', thus not being able to complete a commanded maneuver. The problem of singularities stresses the need to develop a steering logic, which will steer the CMG system away from these singularities with the minimum resources and within the system hardware (gimbal motor) constraints. Many laws have been developed in order to accommodate the problem of singularities with varying degrees of success [4-9, 11]. Most of these have been developed for 4-SGCMGs in a pyramid configuration. A 4-SGCMG system of pyramid arrangement gives the advantage of having a spherical momentum envelope, which results to an almost equal momentum capability in all three axes.



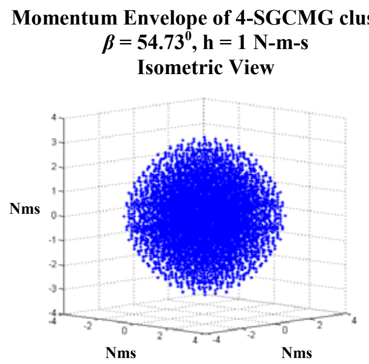


Figure 4: 4-SGCMG cluster in pyramid arrangement and momentum envelope

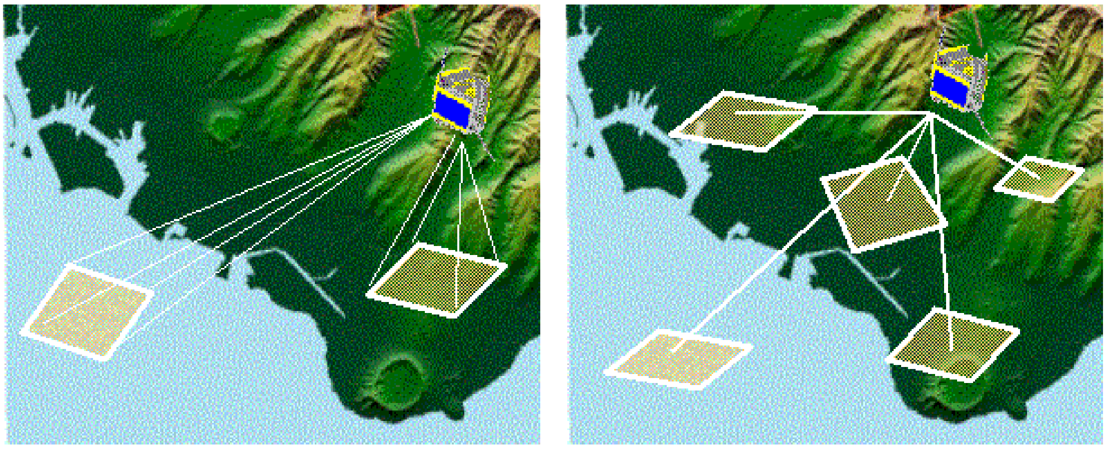


Figure 2: Agile small satellites will increase the amount and value of earth observation and space science data collected

1. <u>CMGs for Agile Small Satellites</u>

CMGs can potentially change the way in which we will develop and operate the small satellites of the future. Agility besides increasing the operational envelope of the spacecraft, will also enable such spacecraft to collect more earth and space science data than before whilst using the same or even less resources. This in practice means a direct increase in the commercial and scientific value of these spacecraft. One of the most severe constraints in small satellite missions is the limited time available for data transmission. CMGs will allow a small satellite to perform off-nadir pointing for substantial larger times, in order to enable it transmit data. This capability will also enable these satellites to transmit more frequent (more often in range of ground stations) to available stations. One of the missions currently designed in the Surrey Space Centre is the Disaster Monitoring Constellation (DMC), which is a constellation of 5 microsatellites each belonging to a different user, but including exchange and use of data received from the 5 ground stations. The use of CMGs in such missions could allow many more frequent opportunities to collect and transmit data, especially when natural disasters occur.

Figure 3: New missions with CMG equipped small satellites: Tactical Imaging. Asteroid tracking, synthetic apertures

CMGs, due to their torque and momentum properties, will allow for the design of a more stable platform. The large, stored angular momentum will be able to sustain and cancel external disturbances to the spacecraft. The use of a constant spinning wheel (instead of reaction wheels with varying speeds) will decrease the small vibrations existent in these spacecraft and increase the pointing accuracy of the satellite.

In all, CMGs can potentially revolutionise small satellite design and operations. It allows new mission scenarios such as asteroid missions, synthesizing large apertures in space with swarms of satellites or tactical imaging to materialise due to their high slew rate capability and can significantly enhance current data collection without any increase in the satellites resources (power, mass, volume, fuel).

2. A low cost, miniature SGCMG cluster for agile microsatellites

A low cost miniature SGCMG cluster has been designed as part of this research. The aim is to investigate the feasibility of using a SGCMG for an enhanced microsatellite from the hardware point of view.

2.1 Slew Maneuver Requirement

The current standard slew maneuver rate for small satellites is in the range of $0.1\text{-}1^0/s$[12, 13]. Future missions indicate a need for an increased slew rate capability. In recent publications[8] it is mentioned that missile tracking satellites and Radar satellites for tracking ground-moving targets will need rapid rotational maneuverability. The French space agency CNES, is working towards developing highly agile satellite replacements of the SPOT remote sensing satellites with its Land Surface Processes and Interaction Mission (LSPIM) [1,2]. Satellite or space station inspectors will require high maneuverability in order to rapidly point to areas of interest or to dock. Asteroid tracking missions also need to rapidly track their targets (asteroids) as required in many space microsatellite missions under consideration. Agile target tracking is the main mission requirement for another small satellite mission for the British Ministry of Defense (MoD), called TOPSAT[16]. All these missions require high slew rates of at least an order of magnitude greater than the current standard of $0.1\text{-}1^0/s$, i.e. more in the $1\text{-}10^0/s$ range. Thus it has become important to develop an actuator that will be able to generate such high slew rates. As a first step towards developing actuators for highly agile spacecraft, an actuator with an average slew requirement of $3^0/s$, will be studied using a SSTL microsatellite platform as a suitable target vehicle. A $3^0/s$ average slew rate means that the satellite used for this analysis will be able to accomplish a 90^0 maneuver in 30s (or 30^0 in 10s). Table 1 provides the characteristics of the satellite (microsatellite) that is going to be used throughout the rest of the analyses, unless stated otherwise.

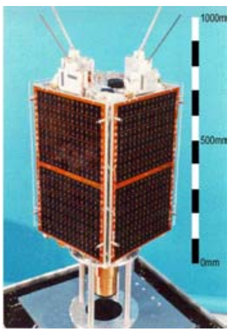


Figure 4: SSTL Microsatellite

Satellite Inertia [I_x, I_y, I_z] (kg-m^2)	[2.5, 2.5, 2.5]
Mass (kg)	50
Average Slew rate (^{0}/s)	3

Table 1: SSTL Microsatellite characteristics

Of all candidate actuators (reaction wheels, momentum wheels, control moment gyros), all of them have as a common factor a spinning rotor, which is the main torque generator. Thus, the slew maneuver speed depends critically on the rotor's (hence motor) torque and momentum capability. Therefore:

$$N_w = I_w \dot{\omega}_w = I_s \ddot{\theta} \qquad (1)$$

where,
N_w is the wheel torque,
I_w is the wheel moment of inertia,
ω_w is the wheel speed
I_s is the spacecraft moment of inertia (Table 1)
$\ddot{\theta}$ is the spacecraft's angular acceleration

All parameters in this thesis are measured with respect to the spacecraft body frame and referenced to the inertial frame.

The requirement is of the spacecraft to be able to perform a 90^0 maneuver in 30s, or for 30^0 in 10s. In order to complete the 30^0 maneuver in 10s there needs to be an acceleration phase (which will take 5s) and a deceleration phase as depicted in Figure 2.4. Thus we make our calculations for 15^0 in 5s:

$$\theta = \frac{1}{2}\ddot{\theta} t^2 \qquad (2)$$

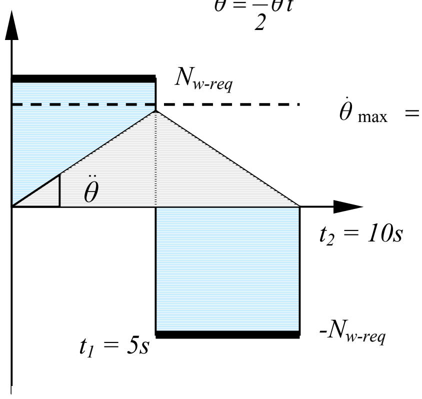


Figure 5: Torque and acceleration diagram for an SSTL microsatellite executing a 30° maneuvre in 10 seconds

$$\frac{\pi}{12} = \frac{1}{2}\ddot{\theta}(5)^2, \quad \ddot{\theta} = 0.021\frac{\text{rad}}{\text{s}^2},$$

with a maximum angular rate of 0.105 rad/s^2

$$N_w = N_{w\text{-}req} = 52.25 \text{ mNm}$$

where,
$N_{w\text{-}req}$ is the required torque needed to achieve the specified maneuver.

2.2 SGCMG Sizing

A 4-SGCMG cluster in pyramid configuration is used in order to attain full 3-axis agile control for an ACS system for a microsatellite. From the previous section it was concluded that a torque of 52.5 mNm is required to perform a 30^0 maneuver in 10s. This requirement is used to size a SGCMG for a microsatellite (Eq. 1):

$$\mathbf{N_{CMG}} = \mathbf{h} \times \dot{\boldsymbol{\delta}} \qquad (3)$$

Sizing the angular momentum of the CMG **h** and the maximum gimbal angles rate $\dot{\delta}_{max}$ (same for all four CMGs) is a trade-off between performance (torque), size and singularity avoidance. One would want to keep the angular momentum as small as possible, since it depends on the inertia of the spinning wheel as well as the speed of rotation of the wheel. This implies that with a larger angular momentum, a larger DC motor will be required, with a heavier disc. On the other hand, the larger the gimbal rate, the larger the δ angle excursions, thus the greater the probability that the CMGs will enter into a singularity. Thus it becomes important to optimise **h** and $\dot{\boldsymbol{\delta}}$ given the mechanical constraints of a practical system. The attitude control model designed in previous work[19] is used to perform and evaluate this trade and to select the optimum values to be used in a CMG system.

From simulations, it has been decided to use a $\dot{\delta}_{max}$ of 6^0/s (or 0.12 rad/s). This value matches the maximum slew rate needed in order to perform a 30^0 maneuver in 10s.

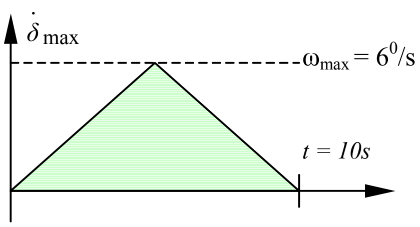


Figure 6: Gimbal rate and angular rate diagram

This selection for $\dot{\delta}_{max}$ ensures that torque amplification is feasible throughout a commanded maneuver. Normally, one can calculate the angular momentum **h**, by using Equation 3 (and get h_0 of each CMG) but this will not enable us to properly size a CMG for a single axis maneuver. This can be explained by analysing the 4-SGCMG cluster trying to do a maneuver about its *x*-axis:

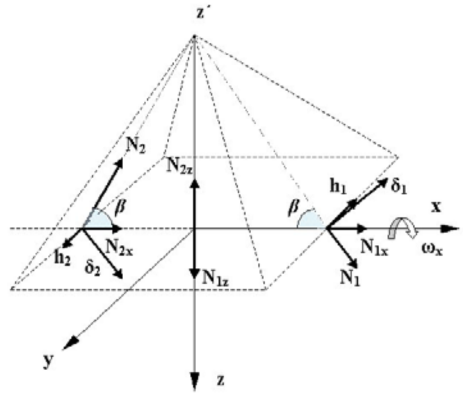


Figure 7: CMG cluster for an *x*-axis maneuver

The torque generated will be:

$$\mathbf{h_1} = h_0 \begin{bmatrix} -\sin\delta_1 \cos\beta \\ -\cos\delta_1 \\ \sin\delta_1 \sin\beta \end{bmatrix} \qquad \dot{\boldsymbol{\delta}}_1 = \begin{bmatrix} -\dot{\delta}_1 \sin\beta \\ 0 \\ -\dot{\delta}_1 \cos\beta \end{bmatrix},$$

$$N_{1x} = h_0\, \dot{\delta}_1 \cos\beta \cos\delta_1$$

$$\mathbf{h_2} = h_0 \begin{bmatrix} -\sin\delta_2 \cos\beta \\ \cos\delta_2 \\ -\sin\delta_2 \sin\beta \end{bmatrix} \qquad \dot{\boldsymbol{\delta}}_2 = \begin{bmatrix} -\dot{\delta}_2 \sin\beta \\ 0 \\ \dot{\delta}_2 \cos\beta \end{bmatrix},$$

$$N_{2x} = h_0\, \dot{\delta}_2 \cos\beta \cos\delta_2$$

Due to symmetric rotation $\delta_1 = \delta_2$ and $\dot{\delta}_1 = \dot{\delta}_2 = \dot{\delta}$:

$$N_x = 2h_0\, \dot{\delta} \cos\beta \cos\delta \qquad (4)$$

Thus, for N_z = 52.5 mNm, $\dot{\delta}_{max}$ = 0.12 rad/s and $\delta = 0^\circ$, h_0 = 0.35 Nms

A value of 0.35 Nms is used to size the disc of the spinning wheel:

$$h_0 = I_{CMG}\omega \qquad (5)$$

The DC motor chosen to be used to spin the disc has a maximum speed of rotation of 20,000 rpm. Thus, a disc with an inertia of 1.7 x 10^{-4} kg-m^2 is needed. Figure 8 depicts the simulation of a microsatellite performing a 30^0 maneuver in 10s with the derived SGCMG parameters. The maneuver is accomplished within 10s. Figure 8b indicates the gimbal angle excursions, not exceeding more than 36^0. The gimbal rates reach a maximum of 6.7^0/s (approximately 0.12 rad/s). The CMG torque and angular momentum values reach the values expected. The spacecraft angular rates also achieve a maximum of 5.4^0/s in order to accomplish the 3^0/s average slew requirement.

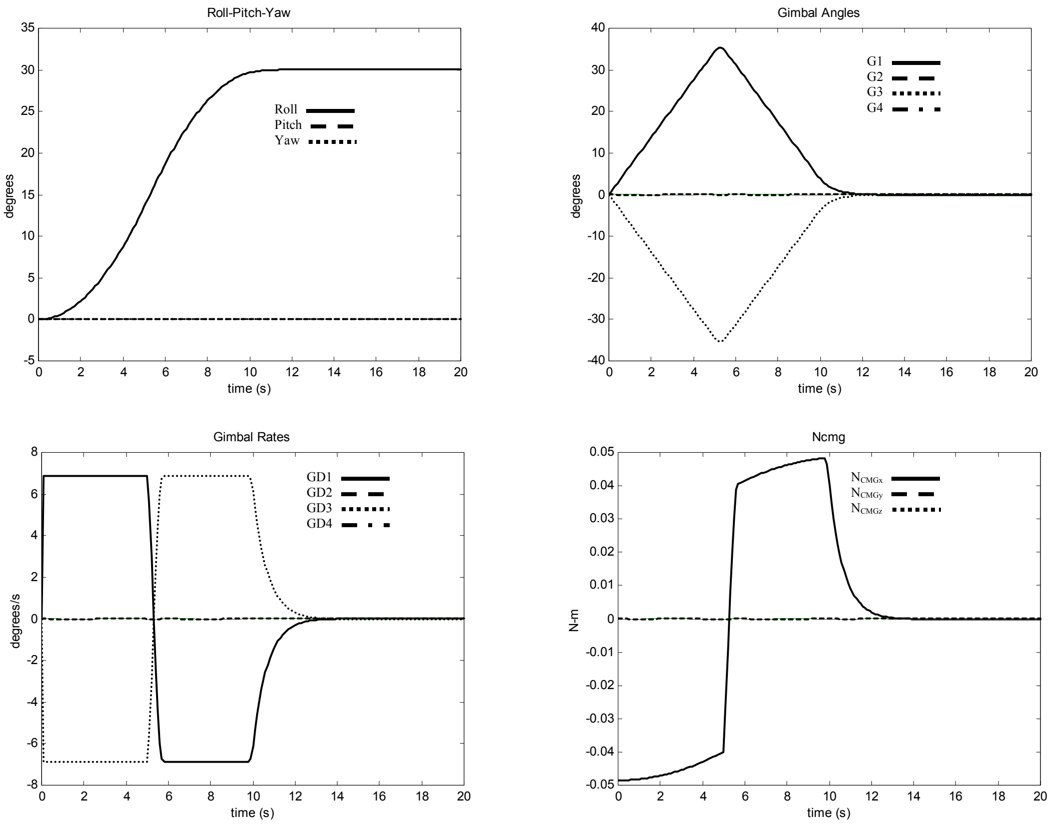
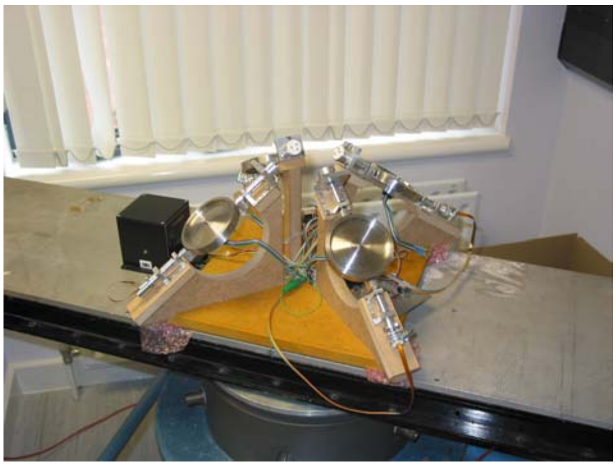


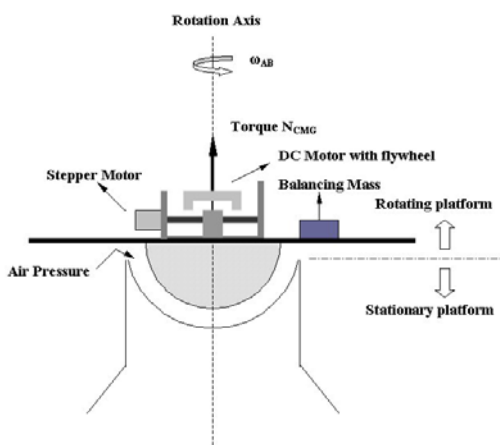
Figure 3: a) Roll-Pitch-Yaw b) Gimbal angles c) Gimbal Rates d) CMG Torque

3.0 SGCMG Cluster Experiments

In order to practically verify the characteristics of CMGs a cluster of four SGCMGs is used with a pyramid skew angle of 54.7º. The CMGs cluster is placed on an air-bearing platform, which allows for rotation about one axis (vertical or *z* axis) without significant friction[19]. An air-bearing platform allows the testing of the dynamical characteristics of a satellite control system on the ground during pre-launch testing campaigns. An Inertial Measurement Unit (IMU), which comprises three gyroscopes, one per axis, is used to record angular rate measurements of the rotating platform. The experiment involves performing a single axis maneuver where two CMGs are used. The experimental set-up of the CMG cluster is depicted in Figures 9, 10 and Figure 11 indicates a block diagram of the experiment performed.



Figures 9: CMG cluster



Figures 10: CMG experimental set-up

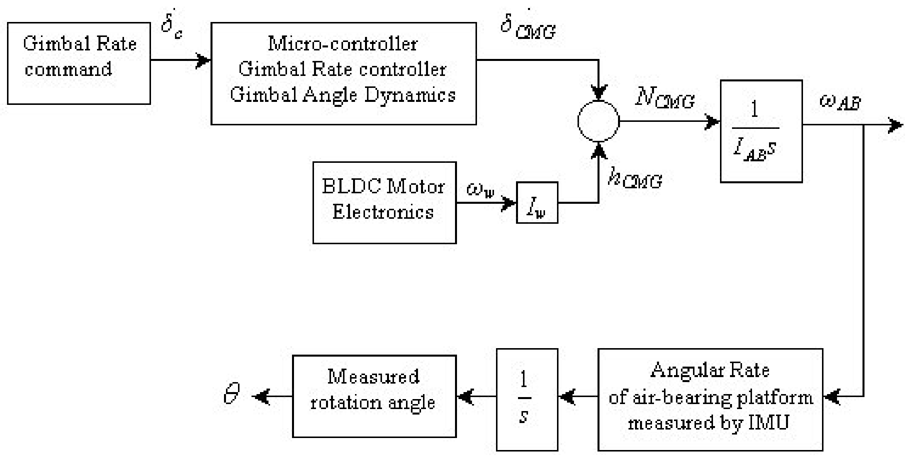


Figure 11: Block diagram of the CMG experiments on the air-bearing platform

The CMG output torque is given by Equation 1. The theoretical values for calculating are attained by using the known angular momentum, **h**, of the SGCMG by using Equation 2 (I_{CMG} and ω are known) and the commanded gimbal rates (Equations are presented again for the readers clarity).

$$\mathbf{N} = \mathbf{h} \times \dot{\boldsymbol{\delta}}$$

$$h_0 = I_{CMG}\omega_w$$

The angular momentum each CMG can produce is 0.35 Nms but due to friction, h_0, is 0.23 Nms.

The experimental values are measured via the relationship derived from the dynamics of the rotation table:

$$I_{AB}\,\dot{\omega}_{AB} = -I_w\,\dot{\omega}_w + N_d \qquad (3)$$

where,

ω_{AB} is the angular speed of the air-bearing rotating platform

ω_w is the angular speed of the CMG disc

N_d is the external disturbance torque

For $N_d = 0$ (due to the air-bearing table) and by knowing the moment of inertia of the air-bearing table I_{AB} (0.8 kg-m^2) the experimental measurements of the angular rate ω_z can be used to calculate the experimental torque of the CMG cluster. Table 2 presents the CMG parameters used in the experiment.

Parameter	Value
DC motor mass	6.5 g
Momentum Wheel	150 g
Gimbal motor mass	9 g
Gimbal Motor Gear box	6 g
Power (Min.-Max.)	0.55-3.00 W
Voltage	5 V
SGCMG Mass	175 g
SGCMG Ang. Mom. h_0 **(**ω_w **~ 11,000 rpm)**	0.35 Nms
Maximum CMG Ang. Mom. $h_{CMG\text{-}max}$	1.1 Nms
CMG avionics	100 g
Mechanical Assembly	200 g
CMG Total Mass (4 SGCMGs + Avionics)	1000 g
CMG Output Torque	52.5 mNm

Table 2: CMG experimental parameters

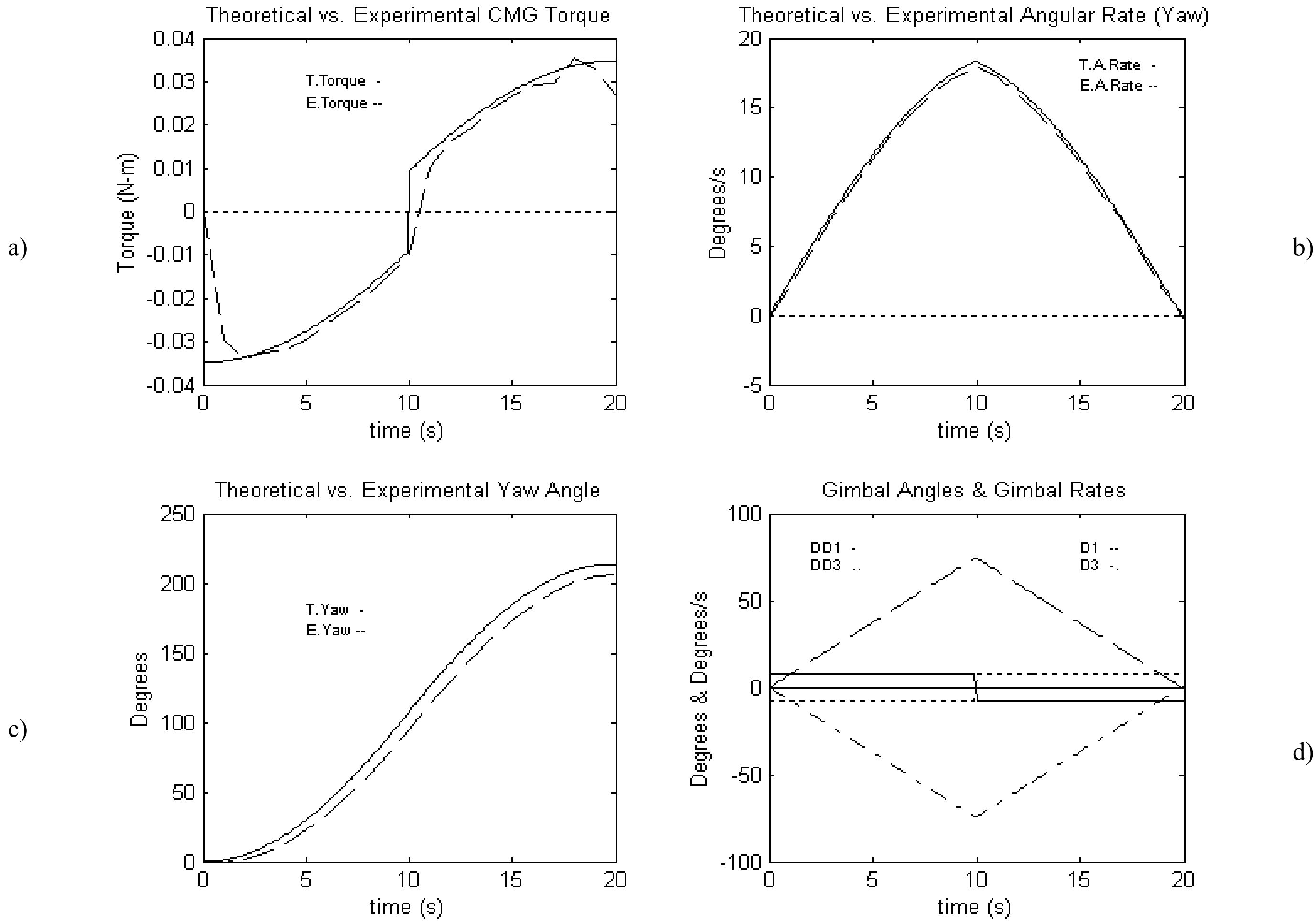


Figure 12: a) Theoretical vs. Experimental CMG Torque b) Theoretical vs. Experimental Yaw c) Theoretical vs. Experimental Angular Rate ω_z (Yaw) d) Gimbal Angles and Gimbal rates (Theoretical)

Figure 12a indicates the theoretical and experimental CMG torques. Due to differentiation of the angular rates, the experimental value for torque starts from zero. The theoretical values are generated from CMG simulations modeled in MATLAB and SIMULINK© which do not take under consideration the wheel and gimbal motor dynamics, or any other internal disturbances such as motor cogging or torque ripple effects. The error between the two curves reaches a maximum of 0.006 Nm and this is mainly due to the disturbances that affect the CMG cluster on the air-bearing (air-bearing bias, friction) and also due to mechanical reasons (CMG stepper motor backlash, micro vibrations, wheel imbalances and small wheel speed variations). Figure 12b presents the angular rates (measured and simulation values) with a maximum angular rate of 17.4º/s (experimental) and a maximum theoretical value of 18.6º/s. Multiple measurements were made and the best individual measurement set was used. The measurements were taken using small sampling rates due to the high angular rates of the rotating platform. The small errors between theoretical and experimental values can be explained from the disturbances mentioned. These errors are within a band of ±0.8 º/s. Figure 12c illustrates the values for the angle θ, the rotation angle of the rotating air-bearing platform caused by the CMG gimbaling. The angle θ expected from simulations is 218.4º whereas the experimental value attained is 209.8º. Considering that the maneuver performed is an open-loop maneuver and coupling the disturbance effects of the air-bearing this result is within an acceptable error of 8.6º. This error in angle θ is expected to significantly decrease if the experiments where to be performed in a more ideal environment (clean room or in vacuum). However, even with the mentioned disturbances and expected small error in the rotation angle θ, the experiments demonstrate the CMG performance for a 0.8 kg-m^2 platform along with the significant torque capability of the CMGs. Figure 12d depicts the gimbal rates fed to the CMG system by the gimbal stepper motors with values of ±7.5º/s which generate gimbal angle excursion reaching ±75º.

4.0 Future enhanced CMGs

Having tested and demonstrated the CMG viability and performance for a microsatellite, an improved version of a SGCMG is currently designed to be accommodated on larger 130 kg enhanced microsatellites. A larger 4 quadrant, 3 phase Brushless DC motor is used together with the same miniature stepper motor of the 4-SGCMG cluster. The CMGs are properly sized for the larger satellite inertias and use a twin disc arrangement for enhanced structural rigidity and performance.

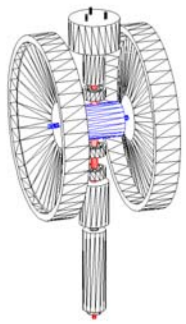


Figure 13: Enhanced CMG

Satellite Inertia [I_x, I_y, I_z] (kg-m^2)	[6.5, 6.5, 5]
Mass (kg)	130
Average Slew rate (^{0}/s)	2

Table 3: SSTL Microsatellite characteristics

This improved CMG is designed to provide an average 2º/s average slew rate. An engineering model has been designed and testing is to commence in the near future. A cluster of two of these CMGs is being designed to fly on a near-future enhanced microsatellite mission as an experimental payload. The CMG cluster will provide rapid pitch axis control and will be able to also operate in a 2-axis momentum wheel mode as well.

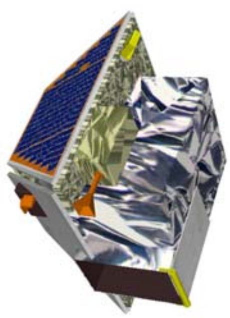


Figure 14: SSTL Microsatellite

5.0 Conclusion

A new practical ACS system based on CMGs has been designed and presented. Practical work confirms the theoretical findings on the advantageous use and performance of CMGs for agile small satellites. A cluster of 4-SGCMGs in pyramid arrangement is used to demonstrate full 3-axis control. The cluster is able to generate a maximum of 36 mNm in normal environmental conditions. With a mass of 1 kg, the CMG cluster can potentially become a very efficient ACS system for agile small satellites, using less resources (mass, volume and electrical power) than conventional technologies (momentum/reaction wheels). A larger, improved CMG has also been designed for the enhanced microsatellite class of spacecraft. A cluster of 2 of these CMGs is under design to be flown as an experimental payload for a near term enhanced microsatellite mission. The use of CMGs will enable small satellites to substantially enhance their capabilities without any increase in power or size. By providing agility, these satellites considerably increase their operational envelope and efficiency and substantially increase the return of earth and science mission data. This can potentially lead into a new way of designing and operating small satellites, making them more versatile and efficient platforms than ever before.

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