Attitude Control for Small Satellites using Control Moment Gyros

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Abstract

In this paper a new 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. A low cost, miniature SGCMG designed for an enhanced microsatellite is analysed. Sizing of a proposed SGCMG indicates the advantages of using CMGs. The SGCMG is able to produce a torque of 9.82 mNm and this is confirmed through experiments performed on an air-bearing table.

Introduction

Many of the space missions will require much more capable spacecraft within smaller sizes. These will include high precision Earth Observation and space monitoring, satellite inspection, distributed platforms, constellations, satellite docking and miniature interplanetary probes. Many of these missions will require agility. Agility considerably increases the operational envelope and efficiency of spacecraft and can substantially increase the return of mission data. Attitude Control Systems (ACS) is an area critical for all types of spacecraft. Designing high performance ACS subsystems for future high precision, agile mission scenarios within the stringent physical size constraints of small satellites is not an easy task. Agility requires fast slew maneuvers of the 1-10^0/s range. It has become evident that current ACS actuators (e.g. momentum wheels, reaction wheels) are not able to provide this degree of agility efficiently. However, Control Moment Gyros are actuators that can support such slew rates, and yet, to date, they have never been used in small satellites.

A low cost, miniature SGCMG for agile microsatellites

A low cost miniature SGCMG 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.

Slew Manoeuvre Requirement

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, the SSTL 'Constella' bus, which is baselined for the TOPSAT mission [4], 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 manoeuvre 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.

Satellite Inertia [I_x, I_y, I_z] (kg-m^2)	[2.5, 2.5, 2.5]
Mass (kg)	130
Average Slew rate (^{0}/s)	3

Table 1 - SSTL E. 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:

$$N_w = I_w \dot{\omega}_W = I_s \ddot{\theta} \tag{1}$$

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 paper 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 manoeuvre in 30s, or for 30^0 in 10s. In order to complete the 30^0 manoeuvres in 10s there needs to be an acceleration phase (which will take 5s) and a deceleration phase. Thus we make our calculations for 15^0 in 5s:

$$\theta = \frac{1}{2}\ddot{\theta}t^2 \tag{2}$$

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

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 manoeuvre.

A 4-SGCMG cluster in pyramid configuration is used throughout this paper as the basis 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 manoeuvre in 10s. This requirement is used to size a SGCMG for a microsatellite:

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

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 [3] 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 manoeuvre in 10s. This selection for $\dot{\delta}_{\max}$ ensures that torque amplification is feasible throughout a commanded manoeuvre. 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 manoeuvre. This can be explained by analysing the 4-SGCMG cluster trying to do a manoeuvre about its *x*-axis:

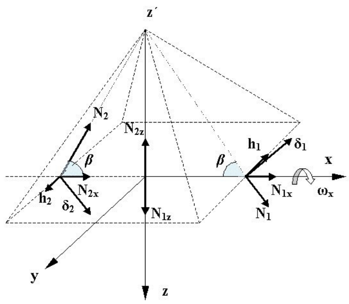

Figure 1 - CMG cluster for an *x*-axis manoeuvre

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 δ = 0°, h_0 = 0.35 Nms

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

$$h_0 = I_{CMG}\omega \tag{5}$$

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. Now that all CMG parameters have been established, these values can be put into the attitude control model [3] designed in order to evaluate the performance of the proposed CMG. Figure 2 depicts the simulation of a microsatellite performing a 30^0 manoeuvre in 10s with the derived SGCMG parameters. The manoeuvre is accomplished within 10s. Figure 2b 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.

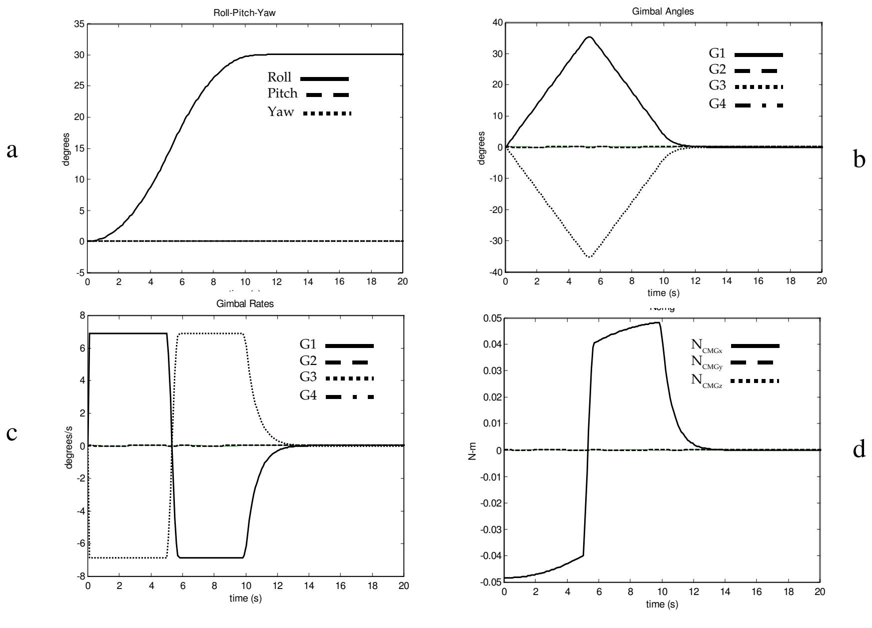

Figure 2 - a) Roll-Pitch-Yaw b) Gimbal angles c) Gimbal Rates d) CMG Torque

SGCMG Experiments

The CMG design proposed and evaluated in the previous section has being built and has been tested to prove the concept of CMGs for microsatellites. The design comprises of an ultra miniature, high performance DC motor, gimballed by a stepper motor. The use of a stepper motor is justified by trying to keep the design simple and reliable. A potentiometer and encoder are used to get readings for the rate of rotation of the DC motor mounted on its shaft. A gear is used with an approximate ratio of 20:1 to reduce the 1.8° step angle and to increase the resolution of the CMG. Two bearings are used to provide structural support to the CMG shafts.

Having designed the electronics to control the DC motor and stepper motors, the CMG is put on an air bearing table. An air-bearing table provides the capability of rotation without significant friction. It is frequently used to test the dynamic characteristics and performance of a model satellite control system during the pre-launch experimental testing campaign on the ground. It is suspended by air, which allows nearly frictionless rotation. The rotational freedom depends on the mechanical structure. The air bearing table used is a single degree of freedom air bearing mounted around a semi-sphere which provides air suspension via 6 holes placed 120° apart in two different levels, which propel air under pressure to slightly lift the rotating part of the table from the stationary part. In order to test the SGCMG the CMG test assembly was put on the air-bearing table. A laser-pointing device was used to reflect on a mirror on the test assembly in order to calculate the angular rate of the rotating platform, which is rotating due to the torque exerted by the SGCMG.

The method used to test the SGCMG was to allow the CMG begin from a known inclined position of 25° from a reference axis parallel to the ground level. The CMG is then commanded to perform a 50° excursion and return to its initial position, thus resulting to a 100° total gimbal angle excursion (50° positive and 50° negative). This will generate a rotation about the air-bearing rotation axis, which we measure by using the laser-pointing device and time with a stopwatch. That allows measuring the average angular rate and angular acceleration of the platform. The period and frequency of these 50° excursions can be varied and various measurements are made in order to evaluate the SGCMGs performance. The theoretical and experimental values of the SGCMG designed are compared. The theoretical values are attained by using the known angular momentum, **h**, of the SGCMG by using Equation 5 (I_{CMG} and ω are known) and the commanded gimbal rates. The experimental values are measured via the relationship derived from the dynamics of the rotation table:

$$I_{AB}\,\dot{\omega}_{AB} = -I_w\,\dot{\omega}_w + N_d \qquad (6)$$

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} (4.4 kg-m^2) the experimental measurements can be used to calculate the experimental torque of the SGCMG.

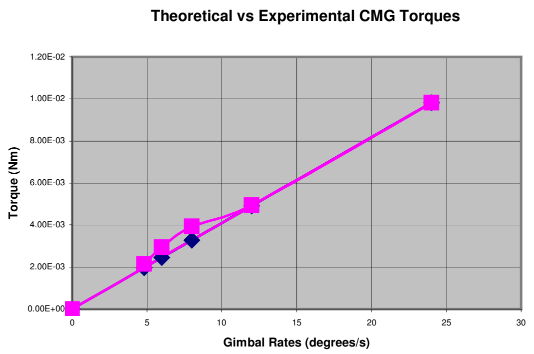

Figure 3 - Theoretical and Experimental CMG Torques

Comparing the theoretical and experimental data, it can be observed that the values are very close to each other with small deviations of error for a few measurements. This can be justified from the low gimbal rates causing long excursions in the measurements of the distance measured from the reflecting laser beam. Due to the small disturbances still existent in the air-bearing table, flywheel imbalances, flexing of the wires, flowing air in the room where the experiment takes place and also due to the small torques being measured, some small errors in measurements are expected. Nonetheless the SGCMG is able to generate a torque of 9.82 mNm with a gimbal rate of 24°/s. The CMG though is capable of producing the required 52.5 mNm torque for a 30° manoeuvre in 10s by simply using a higher gimbal rate or a higher inertia for the CMG disc. For practical purposes a flywheel inertia of 2 x 10^{-5} kg-m^2 was used as well as a DC motor with a maximum angular speed of 11,200 rpm (maximum speed 16,000 rpm). Due to friction the maximum rpm of the motor cannot be obtained unless used in vacuum.

Future work

In the next phase of research a cluster of 4-SGCMGs in pyramid configuration is to be designed. This will focus into making the CMG cluster as compact and robust as possible. A COTS Inertial Measurement Unit (IMU) will also be utilised in order to get better angular rate measurements.

Conclusions

A new actuator for agile small satellites is described in this paper. Future mission scenarios will a rapid slew manoeuvre capability. Current ACS actuators momentum wheels, reaction wheels) are not able to provide this agility on a very efficient way. CMGs can potentially be more capable and efficient actuators than those currently used and are argued in this paper to be the optimum actuator for agile small satellites. A low cost, miniature SGCMG designed for an enhanced microsatellite is studied. Sizing of the proposed SGCMG indicates the advantages of using CMGs. The SGCMG is able to produce a torque of 9.82 mNm and this is confirmed through experiments performed on an air-bearing table. 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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