"Control Techniques for Aerospace Systems"

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METU-AERO
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SPACE AT SURREY

Minisatellites - Microsatellites - Nanosatellites (platforms & payloads)
• Satellite Communications
• Remote Sensing
• Space Science
• Technology Demonstration

POSTGRADUATE EDUCATION
Research Degrees (MSc, PhD)
Short Courses for Industry

Commercial Exploitation
Surrey Satellite Technology Ltd

• 134 professional staff
• 8 faculty
• 27 PhD researchers
• 18 visiting staff
• dedicated space building
## 1.0 Satellite Classification

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Wet Mass</th>
<th>Medium-Large Satellites</th>
<th>Small Satellites</th>
</tr>
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<tbody>
<tr>
<td>Large satellites</td>
<td>&gt;1000 kg</td>
<td></td>
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</tr>
<tr>
<td>Medium satellite</td>
<td>500-1000 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini satellite</td>
<td>100-500 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro satellite</td>
<td>10-100 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nano satellite</td>
<td>1-10 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pico satellite</td>
<td>0.1-1 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femto satellite</td>
<td>&lt;100 gr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**UoSAT-12 Minisatellite**
**Enhanced Microsatellite**
**SNAP Nanosatellite**
2.0 Introduction to ACS for Small Satellites

- **Attitude Control Systems (ACS):** Orientation of a spacecraft in a particular direction (pointing) during a mission, despite external disturbances.
- Need to know s/c attitude (Determination) and then point using an actuator (Control) to desired target.
- Focused on:
  - Low cost, power, mass, volume
  - Avoiding using moving parts
- **Main actuators:**
  - Magnetic torquers/magnetometer
  - Momentum Wheels, Reaction Wheels
  - Thrusters
- **Accuracy:** 0.1-5°
- **Slew rates:** 0.1-0.5°/s
3.0 Slew Rates - Agility (I)

- Current Small Satellite slew rate: 0.1-1°/s
- Need to increase slew rate by an order of magnitude (1-10°/s)
  - Dictated by future missions:
    - Stereo-imaging, tactical imaging (military imaging)
    - Interplanetary probes, formation flying
    - Commercial imaging
  - Technology Development
- Difficult to accomplish with current actuators (reaction/momentum wheels)
  - Large motors/discs
  - Power, volume, mass constraints
- **Agility**: High degree of spacecraft manoeuvrability
- **Agility**: High spacecraft slew rates
3.0 Agility (II)

- Agility substantially increases the operational envelope and efficiency of spacecraft
- Considerable increase in the return of earth and science mission data
- Direct increase in commercial & scientific value of mission
Tactical Imaging & Tracking Moving Objects, Commercial Imaging
Formation Flying, Satellite/Space Station Inspection
Asteroid Missions-Agility
Agility for Small Satellites
Attitude Determination and Control Systems (ADCS)

• Key Subsystem of Spacecraft
• Important for stability and pointing
• Think of a person taking a picture with a camera (blurry pictures if not stable)

• ADCS Systems are complicated:
  – Fusion of software/hardware components
  – Need electronics/aerospace/controls principles

• Brief overview of ADCS components:
  – Stabilisation
  – Sensors for attitude determination
  – Actuators
Spacecraft Stabilisation

Spinner

3-axis
Sensors for Attitude Determination

Star Camera

Gyros

GPS

Sun Sensor

UoSAT-12 Magnetometer
Actuators for Attitude and Orbit Control

Reaction/Momentum Wheels

CMGs

Thrusters
3.0 Agility-Slew Rate Requirement

Assumptions:
- Average 3°/s slew requirement (30° in 10s)
- Use SSTL Microsatellite platform throughout analysis

\[ \theta_{max} = 6^\circ / s \]

\[ N_{w-req} = 52.25 \text{ mNm} \]

- SSTL actuators: 3-20 mNm
- ACS based on RWs:
  - 10% of spacecraft mass
  - 40% of required torque

<table>
<thead>
<tr>
<th>Actuator</th>
<th>CMG</th>
<th>RW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Inertias (kg-m²)</td>
<td>[2.5, 2.5, 2.5]</td>
<td>[2.5, 2.5, 2.5]</td>
</tr>
<tr>
<td>Satellite Mass (kg)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Torque (mNm)</td>
<td>32.25</td>
<td>20</td>
</tr>
<tr>
<td>Actuator Mass (kg)</td>
<td>~1</td>
<td>4</td>
</tr>
<tr>
<td>Slew Rate (°/s)</td>
<td>3</td>
<td>1.85</td>
</tr>
</tbody>
</table>
4.0 Motivation

Motivation:

– Required slew rate can’t be supplied efficiently by current technologies
– Need to develop an alternate, more capable actuator based on Control Moment Gyros

Goal

– Develop a Control Moment Gyro (CMG) based Attitude Control System (ACS) for Agile Small Satellites
  1. Proving the viability of CMGs in an ACS system for Small Satellites
  2. Developing a low-cost, miniature Single Gimbal Control Moment Gyro (SGCMG) for Small Satellites
5.0 CMGs for Small Satellites

CMG Background

- **Actuators, ‘Torque Amplifiers’**
- **A momentum wheel, gimballed in 1 or 2 axes**
  - Single-Gimbal CMG (SGCMG)
  - Double-Gimbal CMG (DGCMG)
  - Variable-Speed CMG (VSCMG)
- **Disadvantages**
  - Mechanical Complexity, expensive
  - Singularities (No Torque generation)
  - Size
- **Spacecraft Heritage**
  - KH-11, KH-12
  - Skylab, MIR, ISS
  - Honeywell
  - Alcatel, Astrium (France)
  - Have not flown on commercial s/c yet
5.1 CMG Research

- **B. Wie:**
  - Provides fundamentals of CMGs
  - Using PID control logic (various) for non-linear CMG control
  - Survey of current singularity avoidance laws
  - Novel singularity avoidance law based Singularity Robust law and using modulation functions (deterministic dither)

- **Vadali, S.R.:**
  - Derive CMG equations for a N-cluster of SGCMGs
  - Proves that a family of initial (preferred) gimbal angles can avoid singularities

- **Bedrossian, N.S., Margulies, G. and Auburn, J.N.:**
  - CMG fundamentals, description of null motion & singularities
5.2 4-CMG ‘pyramid’ Cluster

4-SGCMGs-pyramid, $\beta = 54.74^\circ$ : $h_{\text{CMG-max}} = h_0[3.15, 3.15, 3.26]^T$ N-m-s

$$h = \sum_{i=1}^{4} H_i(\delta_i) = \begin{bmatrix} -c\beta \sin \delta_1 & -\cos \delta_2 & c\beta \sin \delta_3 & \cos \delta_4 \\ \cos \delta_1 & -c\beta \sin \delta_2 & -\cos \delta_3 & c\beta \sin \delta_4 \\ s\beta \sin \delta_1 & s\beta \sin \delta_2 & s\beta \sin \delta_3 & s\beta \sin \delta_4 \end{bmatrix}$$
5.2 Mathematical description of a 4-CMG Cluster

- **Rotational Equations of Motion:**
  \[ \dot{H}_s + \omega \times H_s = N_{ext} \]
  - \( H_s \): s/c angular momentum
  - \( \omega \): s/c angular velocity

- **Spacecraft Angular Momentum:**
  \[ H_s = I\omega + h \]
  - \( h \): CMG angular momentum
  - \( I \): s/c inertia matrix

- **Combining above equations:**
  \[ \dot{h} = -u - \omega \times h \]
  - \( u \): Torque control vector

- **SGCMG h:** \( h = h(\delta) \)
- **Need 4-SGCMGs for full 3-axis control**
5.3 Singularity Avoidance Steering Laws

\[ \dot{h} = A \dot{\delta} \]

- Where \( A \) is a 3 x 4 Jacobian Matrix

\[
A = \begin{bmatrix}
- c\beta \cos\delta_1 & \sin\delta_2 & c\beta \cos\delta_3 & -\sin\delta_4 \\
\sin\delta_1 & -c\beta \cos\delta_2 & \sin\delta_3 & c\beta \cos\delta \\
s\beta \cos\delta_1 & s\beta \cos\delta_2 & s\beta \cos\delta_3 & s\beta \cos\delta_4 
\end{bmatrix}
\]

- Inverse Kinematic Solution (Pseudoinverse)

\[
\dot{\delta} = A^+ \dot{h} = A^T (AA^T)^{-1} \dot{h}
\]

- Goal is to generate commanded torques and to also avoid ‘singular’ sets of gimbal angles, where no torque is produced
- ‘Steer’ angles to more favourable directions, escape, avoid or transit through singularities
• In MATLAB® and SIMULINK®
• Satellite Model, CMG Dynamics, Quaternion Feedback Controller

- Used to study the behaviour of a CMG attitude control system
- Test Singularity Avoidance laws, try new ones
- Minisatellite, Microsatellite and Nanosatellite models used
5.4 CMG ACS Simulations (II)

Attitude Control Model

- **CMG Steering Logic**
  - $\delta$
  - $h_{ref}$

- **Momentum Generator**
  - $u$

- **Integration**
  - $\int dt$
  - $h_{CMG}$

- **Satellite Dynamics**
  - $\frac{dh_{CMG}}{dt} = N_{CMG}$
  - $N_{EXT}$
  - Roll Pitch Yaw

- **Feedback Controller**
  - $\omega_{bi}$
  - $q$
  - $\omega_{ref}$
  - $q_{ref}$

Dr. Vaios J. Lappas

METU Aerospace Seminar

May 8, 2003
5.4 CMG ACS Simulations (III)

**Microsatellite**

-65° Roll maneuver

\[
[I_x, I_y, I_z] = [10, 10, 10]
\]

kg-m²s

\[
[\delta_1, \delta_2, \delta_3, \delta_4] = [70, 0, -70, 0]
\]
degrees

Replicate elliptic singularity

‘Gimbal lock’: s/c drifts
**Microsatellite**

-65° Roll maneuver

\[
[I_x, I_y, I_z] = [10, 10, 10] \text{ kg-m}^2\text{s}
\]

\[
[\delta_1, \delta_2, \delta_3, \delta_4] = [70, 0, -70, 0] \text{ degrees}
\]

**Replicate elliptic singularity**

Gimbal Angles

Gimbal Angles lock out due to s/c drift

‘Gimbal lock’
6.0 CMG Sizing for a Microsatellite

- 4-CMG cluster in pyramid configuration for full 3-axis control
- Main requirement: Generate $N_{w\text{-req}} = 52.25 \text{ mNm (30° in 10s)}$

For a SGCMG: $N_{CMG} = h \times \dot{\delta}$

- Selection of $h$ and max. gimbal rate is a trade-off between performance, size and singularity avoidance
- Keep $h$ as small as possible (less mass, volume)
- Avoid using large gimbal rates leading to large gimbal angle excursions, thus singularities
- A max. gimbal rate of 7.5 °/s is used which is larger than the max. angular rate of satellite when doing a 30° manoeuvre in 10s
- Ensures torque amplification throughout a manoeuvre
- Simulations for a 30° manoeuvre in 10s
6.1 CMG Simulations for a Microsatellite

- Simulations confirm the ability of the CMGs to provide a 3°/s average slew rate to a microsatellite
- Maximum gimbal angle excursions reach ±36°
- Maximum torque of ~ 50 mNm required
- Simulations were used in an iterative process to determine the best trade in performance/hardware design
- Sizing a CMG, is a trade between the CMG mass, average slew rate requirement, maximum gimbal rate, singularity avoidance and hardware constraints
- Theoretical work indicates some of the benefits of the CMGs for small satellites:
  - Torque/slew rate capability
  - Angular Momentum capability
- Based on the CMG simulations, the CMG design parameters are specified
6.2 CMG Cluster Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC motor mass [Faulhaber 1525E]</td>
<td>30 g</td>
</tr>
<tr>
<td>Momentum Wheel</td>
<td>150 g</td>
</tr>
<tr>
<td>Gimbal motor mass [P10]</td>
<td>9 g</td>
</tr>
<tr>
<td>Gimbal Motor Gear box [R10]</td>
<td>6 g</td>
</tr>
<tr>
<td>Potentiometer [Sector]</td>
<td>10 g</td>
</tr>
<tr>
<td>Couplers (2)</td>
<td>10 g</td>
</tr>
<tr>
<td>Power (Min.-Max.)</td>
<td>TBD</td>
</tr>
<tr>
<td>Voltage</td>
<td>5-12 V</td>
</tr>
<tr>
<td>SGCMG Mass</td>
<td>200 g</td>
</tr>
<tr>
<td>SGCMG Ang. Mom. ( h_0 (\omega_w = 20,000 \text{ rpm}) )</td>
<td>0.35 Nms</td>
</tr>
<tr>
<td>CMG avionics</td>
<td>50 g</td>
</tr>
<tr>
<td>CMG Total Mass</td>
<td>( \sim 1000 \text{ g} )</td>
</tr>
<tr>
<td>CMG Output Torque</td>
<td>52.25 mNm</td>
</tr>
</tbody>
</table>
7.0 Developing a Low-Cost, Miniature CMG for Small Satellites

The main aims are:

1. To **practically** confirm the theoretical work (simulations) performed
2. To validate the viability of using CMG’s as actuators on a microsatellite in a practical way
3. To confirm the agility and power efficiency that CMGs can potentially provide to microsatellites

- Achieve 52.25 mNm Torque, Low, cost, power, size, mass, use COTS
- Use a staged approach:
  1. A Single Gimbal CMG pre-prototype (Mk.I)
     - Demonstrate concept
     - Try various technologies (DC motors, stepper motors)
  2. Cluster of 4-CMGs (Mk. II)
     - Use ‘mission like’ motors
     - Demonstrate CMG benefits (torque, ang. momentum, power, mass)
     - Sized for a SSTL 50 kg microsatellite (e.g. PICOSAT)
7.1 CMG Mk.I Testbed

- Potentiometer
- Disc
- Encoder
- Step angle reduction disc
- API 12° Stepper Motor & Gear Box
- HSX 1.8° Stepper Motor
7.2 CMG Mk.I
7.3 Air Bearing Experiments

- Air-bearing table provides the capability of rotation without significant friction
- Used to test the dynamic characteristics and performance of a model satellite control system during the pre-launch experimental testing campaign on the ground
- Suspended by air, allows nearly frictionless rotation
7.4 CMG Mk.I Experiment (I)

- Operate CMG from a known angle $\theta_0$ of 25° between the spin axis and the horizontal
- Perform a 50° excursion and return to its initial position
- This will generate a rotation about the air-bearing rotation axis
7.4 CMG Mk.I Experiment Animation

- CMGs rotate air-bearing platform
- Use stopwatch to time angular displacements
- Measure laser beam dot distance
- Use trigonometry to calculate the angular rate of rotating platform
7.4 CMG Mk.I Testing (IV)

Rotation of CMG & rotation platform ($N_{CMG} = 8.84$ mNm)
7.4 CMG Mk.I Testing (IV)

Theoretical vs Experimental CMG Mk.I Torques

- **Theoretical Torque:** \( N_z = h \dot{\delta} \cos\delta_0 \)

- **Experimental Torque:** \( N_{CMG} + N_d = -I_{AB} \dot{\omega}_{AB} \)
7.4 CMG Mk.I Testing (V)

- Theoretical CMG Torque value expected for a gimbal rate of 24°/s is 9.82 mNm
- Experimental value of 8.84 mNm and results to a difference (error) of 9.97%
- Errors due to air-bearing table bias, flywheel imbalances, flexing of the wires, aerodynamics friction
- Maximum angular speed is 11,200 rpm (maximum speed 16,000 rpm) due to aerodynamics friction, less angular momentum

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMG E. Microsat</th>
<th>RW E. Microsat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of s/c (kg)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Type of actuator</td>
<td>1 CMG</td>
<td>1 RW</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>~320</td>
<td>1000</td>
</tr>
<tr>
<td>Power Av. Per actuator (W)</td>
<td>0.1-1.2</td>
<td>0.8-3.5</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>5-12</td>
<td>12-16</td>
</tr>
<tr>
<td>Max.Ang. Mom. (Nms)</td>
<td>0.0235</td>
<td>0.36</td>
</tr>
<tr>
<td>Max. Torque (mNm)</td>
<td>8.84</td>
<td>10</td>
</tr>
<tr>
<td>Sat. Inertias (kg-m²)</td>
<td>[2.5, 2.5, 2.5]</td>
<td>[2.5, 2.5, 2.5]</td>
</tr>
<tr>
<td>Average slew rate (°/s)</td>
<td>1.23</td>
<td>1.31</td>
</tr>
<tr>
<td>Min. time for 30° (s)</td>
<td>24.45</td>
<td>22.876</td>
</tr>
</tbody>
</table>
7.5 CMG Mk.II

- Having tested the capability of the Mk.I CMG, another CMG is designed as part of a 4-CMG cluster, the CMG Mk.II. The CMG Mk.II utilizes:
  - A different and more powerful BLDC motor with integrated electronics (Faulhaber 1525 BRE)
  - A larger flywheel (angular momentum), properly sized to generate the required torque on the Mk.II CMG ($I_{CMG} = 1.7 \times 10^{-4}$ kg-m²)
  - The same stepper/gimbal motor (Escap P010/R10) as in the Mk.I
  - New electronics based on a C515 Microcontroller
- Components (motors etc.) can be space graded
- CMG Cluster performance is evaluated through air-bearing experiments
CMG Cluster Layout

- Brushless Motor
- Coupler 2
- Potentiometer
- CMG Flywheel
- Coupler 1
- Gimbal (Stepper + Gearbox) Motor
- $\beta = 54.74^\circ$
7.5 CMG Mk.II Electronics

EPROM: Erasable Programmable ROM
SM: Stepper Motor
BDCM: Brushless DC Motor
CK: Clock
F/H: Full/Half step mode
TLC: Telecommand
TLM: Telemetry
DIR: Direction

δ : Stepper Motor gimbal rate
7.6 Single-axis manoeuvre with two CMGs

\[
\begin{align*}
\mathbf{h}_1 &= h_0 \begin{bmatrix}
-\sin \delta_1 \cos \beta \\
-\cos \delta_1 \\
\sin \delta_1 \sin \beta
\end{bmatrix} \\
\mathbf{h}_2 &= h_0 \begin{bmatrix}
-\sin \delta_2 \cos \beta \\
\cos \delta_2 \\
-\sin \delta_2 \sin \beta
\end{bmatrix}
\end{align*}
\]

\[
\begin{bmatrix}
\dot{\delta}_1 \\
\dot{\delta}_2
\end{bmatrix} = \begin{bmatrix}
-\delta_1 \sin \beta & 0 \\
-\delta_1 \cos \beta & 0
\end{bmatrix}
\]

\[
\begin{bmatrix}
N_{lx} \\
N_{lx}
\end{bmatrix} = h_0 \begin{bmatrix}
\dot{\delta}_1 \\
\dot{\delta}_2
\end{bmatrix} \cos \beta \cos \delta
\]

Due to symmetric rotation

\[
\begin{align*}
\delta_1 &= \mathrm{and} \\
\dot{\delta}_1 &= \dot{\delta}_2 = \dot{\delta}
\end{align*}
\]

\[
N_x = 2h_0 \dot{\delta} \cos \beta \cos \delta
\]

Theoretical CMG Torque = \( N_x = 2h_0 \dot{\delta} \cos \beta \cos \delta \)

Experimental CMG Torque = \( N_{\text{CMG}} + N_d = -I_{AB} \omega_{AB} \)

\( I_{AB} = 0.8 \text{ kg-m}^2 \)
7.7 Experimental Set-up
Block Diagram
7.8 Experimental Set-up
7.9 CMG Mk.II Experiment
7.9 CMG Mk.II Results

- Do not take under consideration the wheel and gimbal motor dynamics, or any other internal disturbances such as motor cogging or torque ripple effects.
- Torque error 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, aerodynamic friction)
  - High bandwidth-mechanical reasons (CMG stepper motor backlash, micro vibrations, wheel imbalances and small wheel speed variations)
  - IMU-Gyro noise
- The rotation angle $\theta$ expected from simulations is 218.4º whereas the experimental value attained is 209.8º.
- Open-loop maneuver and the disturbance effects of the air-bearing result to an acceptable error of 8.6º.
7.10 Electrical Power Consumption

- Electrical power consumption is important for small satellite development and operations.
- Literature, such as [Schaub 1998], [Schaub 2000], [Roser 1997], [Salenc 2000] mention that CMGs require less electrical power than other actuators such as reaction/momentum wheels.
- No theoretical or practical support to this claim.
- A comparison is conducted to compare RW vs. CMG power consumption.
- A microsatellite 10 mNm RW, minisatellite 20 mNm RW and 52.25 mNm CMG.
- 40° single-axis manoeuvre (1 RW, 2 CMGs) for all 3 actuators/platforms.
- In-orbit data used for RWs (Tsinghua-1 RW, UoSAT-12 RW) and vacuum power measurements for CMG.
- Measurements are normalised to a 1 kg-m² MOI.
- Energy index is introduced to compare actuators.
7.11 CMG Electrical Power Consumption

- CMGs perform the 40º manoeuvre in 20s
- Identical to previous experiments
- Measurement is for all 4 stepper/gimbal motors + BDCM
## 7.12 RW Electrical Power Consumption

<table>
<thead>
<tr>
<th></th>
<th>Tsinghua-1 RW</th>
<th>UoSAT-12 RW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturer</strong></td>
<td>SSTL (3)</td>
<td>SSTL (2)</td>
</tr>
<tr>
<td></td>
<td>Ithaco (1)</td>
<td></td>
</tr>
<tr>
<td><strong>Quantity</strong></td>
<td>3 units</td>
<td>3 units</td>
</tr>
<tr>
<td></td>
<td>(X/Y/Z)</td>
<td>(X/Y/Z)</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Brushless DC motor</td>
<td>Brushless DC motor</td>
</tr>
<tr>
<td></td>
<td>Dry lubricated bearings</td>
<td>Dry lubricated bearings</td>
</tr>
<tr>
<td><strong>Operation Range</strong></td>
<td>+/- 0.36 Nms @</td>
<td>+/- 4 Nms @</td>
</tr>
<tr>
<td></td>
<td>+/- 5000 rpm</td>
<td>+/- 5000 rpm</td>
</tr>
<tr>
<td></td>
<td>+/- 0.010 Nm max</td>
<td>+/- 0.02 Nm max.</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>0.2-3 W (zero to max. accel.)</td>
<td>2.8-14.6 W (zero to max. accel.)</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Speed controlled</td>
<td>Speed controlled</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>+/- 1 rpm</td>
<td>+/- 1 rpm</td>
</tr>
</tbody>
</table>
7.13 Tsinghua-1 RW Maneuvre & Electrical Power Consumption

Tsinghua-1 Pitch

Tsinghua-1 RW Absolute Electrical Power Consumption

E. Power
A.E. Power
7.14 UoSAT-12 RW Maneuvre & Electrical Power Consumption

UoSAT-12 Roll

UoSAT-12 RW Absolute Electrical Power Consumption
### 7.15 Electrical Power Consumption Experimental Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UoSAT-12</th>
<th>Tsinghua-1</th>
<th>CMG</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOI (kg-m²)</td>
<td>40</td>
<td>2.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Time (s)</td>
<td>200</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>Torque (mN-m)</td>
<td>20</td>
<td>10</td>
<td>52.25</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>3.2</td>
<td>1</td>
<td>0.585¹</td>
</tr>
<tr>
<td>Avg. Power (W)</td>
<td>2</td>
<td>0.45</td>
<td>1.61</td>
</tr>
<tr>
<td>Scaled Power (W-kg-m²)</td>
<td>0.05</td>
<td>0.16</td>
<td>0.39</td>
</tr>
<tr>
<td>Scaled Energy (J/kg-m²)</td>
<td>10</td>
<td>27</td>
<td>7.85</td>
</tr>
</tbody>
</table>

¹ Mass for two CMGs, unpackaged

- Single axis 40° manoeuvre
- Energy index reflects the energy accumulated during a manoeuvre on a normalized 1 kg-m² MOI platform
- CMGs prove to be the least power consuming actuator with an energy index of 7.85
- 21.5 % more efficient than the UoSAT-12 RW power consumption and 70.9 % more efficient than the Tsinghua-1 RW
7.16 CMG Experiments – Some Conclusions

- Practical work confirms the theoretical findings on the advantageous use and performance of CMGs for agile small satellites
- Two CMGs designed (Mk.I, Mk.II)
- CMGs were evaluated in air-bearing experiments replicating single-axis maneuvers
- CMG Mk.I generated a max. torque of 8.84 mNm, CMG Mk.II a max. torque of 38 mNm, during air-bearing experiments
- Experiments indicate the better electrical power consumption when utilizing a CMG cluster when compared to a RW system
- CMG Mk.II maximum power was found to be 1.614 W
- CMGs are shown to be more power efficient by at least 21.5 % from reaction wheels, with a mass saving of 41.5 % to the smallest (Tsinghua-1) RW
- With a mass of about 1.17 kg CMGs were shown in a practical way to potentially be an efficient and highly capable means of controlling agile microsatellites
8. Application: BILSAT CMG
CMGs for BILSAT-1

- TUBITAK-BILTEN initiated a call for Turkish and SSTL payloads for BILSAT-1
- Numerous payloads suggested
- Payloads selected:
  - Turkish: Coban, Gezgin
  - SSTL: Propulsion, GPS Attitude Determination
  - SSC/SSTL: CMGs…
- Payload Selection: September 2001
- Unofficial approval for CMGs: June 2002
- Time to design CMGs: 6 months! (not…!)
- Payload: A twin (2)-CMG cluster for rapid pitch axis control
BILSAT Payloads

Primary mission: Imaging

- Multi spectral
  - RED: 26 m ground sampling distance
  - BLUE: 26 m ground sampling distance
  - GREEN: 26 m ground sampling distance
  - NIR: 26 m ground sampling distance

- Panchromatic: 12 m ground sampling distance

Secondary mission:
- Store and forward communications
BILSAT Additional Payloads (I)

Maximize the profit gained from this technology transfer programme

**COBAN**
- Multi band camera;
- 80 m resolution;
- 9 channels;
- SQM model of coban

**GEZGIN**
- JPEG2000 DSP Card;
- Real Time image compression;
A propulsion system will be installed on the satellite to make semi major axis corrections. A single thruster fires through the Centre of Gravity to perform orbit change manoeuvres.

System Features
- Propellant - butane
- System dry mass < 6kg
- Propellant mass = 2.3 kg
- 15 Watt resistojet thruster
- Thrust ~ 50 mN
- Delta V ~ 9 m/sec
GPS Receiver

A GPS receiver:
- To give position knowledge = +/- 50 m
- To perform attitude determination = +/- 1 degree

Control Moment Gyro (CMG)

A Control Moment Gyro to improve the agility of the satellite
- Rapid Pitch axis control (2°/s)
BILSAT-1 Satellite Architecture

- **BILSAT-1**: a small satellite based on enhanced micro satellite platform of SSTL

**Core**: standard SSTL self supporting stack of equipment boxes

**Below earth Facing Facet**: enclosure that holds some of the customer built payloads

**Nano modules**: There are also nano modules which are non structural elements
BILSAT-1 Project Status

- Structure qualification tests successful

- Spacecraft in AIT
- EMC Testing this week
- TVT
- Vibrations
- Launch scheduled for July
BILSAT Attitude Determination and Control System (ADCS)
BILSAT can achieve
- attitude control +/- 0.02 deg
- attitude knowledge of 0.006 deg

BILSAT sensors
- four sun sensors,
- four rate sensors,
- two magnetometers
- two star cameras

BILSAT actuators
- four reaction wheels,
- three torque rods,
- gravity gradient boom

A GPS receiver is also used to obtain orbital position information of +/-50 m
## BILSAT ADCS Subsystem (II)

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Performance</th>
<th>Constraints</th>
</tr>
</thead>
</table>
| Star Camera                | SSTL - Altair-HB| Field of view: 15.74° x 10.53°  
Pointing accuracy (<15 arcsec 1 sigma)  
Sensitivity: Down to mag 6.0  
Operating bandwidth: 1Hz  
Max tracking rate: 0.5 %    | Mass: 1.7 kg (including baffle)  
Size: 150 x 150 x 285 mm (including baffle)  
Power Supply: 16-50 VDC  
Power: 2.8W (@ 28V) average  
Temperature: -10 to +50°C |
| 2-Axis Sun Sensor          | SSTL           | Field of view: 60 x 60  
Pointing accuracy: 0.5 deg     | Mass: 300 g  
Dimensions: 95 x 107 x 35 mm  
Operating Temp: -50 to +80 degC |
| Solid-Sate Rate Sensors (Gyros) | BAE - SiRRS | Rate Range: ± 50 deg/s  
Long-term Bias Stability: 0.2 deg/s over 1 year  
Bias Stability: 0.002 deg/s over 100s  
Output Noise: 0.01 deg/s/\sqrt{Hz} | Mass: <35 g  
Size 31.6 x 31.6 x 17.2 mm  
Supply Voltage: +/- 5V  
Operating Temp: -40 to +75 degC |
| Reaction Wheels            | SSTL           | Angular Momentum: 0.42 Nm  
Torque: 10 mNm                  | Mass: 1.1 kg  
Dimensions: 100 x 101 x 92.5 mm  
Power: 24-32V  
1.2 W @ constant speed  
5.6 W @ Max Accel  
0.8 W @ Zero Speed |
CMG Design
• **Attitude Actuator**
  – High torque capability, High stability
  – Exceptional performance for small satellite
    – Fast slews (30deg in 15s for 130kg spacecraft)
    – E.g for tactical imaging, TDI, target tracking
  – Developed by University of Surrey/SSTL/ESA/BILTEN
  – First flight on BILSAT Q3 2003

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>135 x 155 x 190 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.2kg</td>
</tr>
<tr>
<td>Power</td>
<td>12W peak</td>
</tr>
<tr>
<td>Torque</td>
<td>95mNm</td>
</tr>
</tbody>
</table>
BILSAT CMG Requirements

- 2°/s average slew rate capability (pitch axis)
- Demonstrate the principle of a CMG
- Has to fit in the available volume on BILSAT-1
- Mass \leq 1.5\text{kg} per CMG
Agility-Slew Rate Requirement

- **Assumptions:**
  - Average 2°/s slew requirement (40° in 20s)
  - Use BILSAT-1

\[ \dot{\theta}_{\text{max}} = 4\,^\circ / s \]

\[ N_{\text{w-req}} = \frac{\theta_{\text{max}}}{4} \]

\[ N_{\text{w-req}} = \sim 95\, \text{mNm} \]

- SSTL actuators: 3-20 mNm
- ACS based on RWs:
  - 10% of spacecraft mass
  - 40% of required torque
For a 2°/s average slew rate capability (pitch axis) for a 130 kg platform, a 95 mNm torque is required.

Twin CMG payload in parallel configuration

CMG h = 0.28 Nms, Flywheel speed operating at 16,900 rpm, gimbal rate of 9°/s

Can vary flywheel speed and gimbal rate (> 9°/s)
CMG Parameters: $h_{\text{cmg}} = 0.28 \text{ Nms}$, $(I_x, I_y, I_z) = 10 \text{ kg-m}^2$
CMG Mechanics

Shaft encoder
Torsion Spring
Main support bearings
CMG Mechanics

Support structure
CMG Mechanics

Enclosed control electronics

Containment enclosure
CMG Mechanics - Mass

- Mass ~ 2.2 kg per CMG
  - 420g Phytron Motor
  - 100g Faulhaber Motor
  - 90g ‘Flywheel’ (aluminium)
  - 100g Counterbalance (brass)
  - 500g Electronics (in enclosure)
  - 400g Containment enclosure
  - 200g Support bearings
  - 200g Axle, interface structure, fasteners, cable, etc
    - (all figures approximate to show breakdown)
Other CMG Activities

• Working on BILSAT CMG payload exploitation
  – In-orbit data, compare CMGs to RWs, use CMGs as RW/MW/VSCMG
• Developing a Closed loop, hardware-in-the-loop, CMG cluster simulator
  – Constrained 3-axis simulator
  – 4-CMGs in pyramid configuration
• CMGs selected as an experimental payload on ESA’s Proba II research satellite
• Developing CMGs for Minisatellites (ESA)
• Developing new CMG algorithms, Singularity Avoidance schemes, non-linear control strategies
• Modelling of CMG motor dynamics
• Collaboration with Prof. B. Wie (ASU) and Prof. P. Tsiotras (Georgia Tech.)
• Collaboration with METU (Aerospace)?
9. Future Work

- Planetary Ascent Vehicles (PAV): Small Rockets…
- Mars/planetary sample return missions will require some means to transport samples of planetary soil back to earth
- Need to ferry these samples from the planet’s surface to an orbiting return spacecraft
- Need to develop a small rocket to take a 1 kg sample to a low Mars orbit (LMO)
- Surrey working on the conceptual (systems) design and Guidance, Navigation and Control System (GNC)
- GNC system baseline configuration: TVC, single cold gas engine, roll thruster, IMU
9.1 Planetary Ascent Vehicles (PAV)
9.2 Planetary Ascent Vehicles (PAV)

- Develop GNC system in MATLAB/Simulink
- Perform systems analysis of PAV:
  - 1 kg sample payload
  - 3 Astronauts as payload
- Demonstrate concept viability using software//visualisation tools
- Demonstrate Thrust Vector Control (TVC) GNC principles with closed-loop, hardware-in-the loop experiments
- Developing the software/hardware for the experiments
9.2 Micro-UAVs

- New research topic
- Use Surrey’s innovative, low cost design approach
- Design a micro UAV (mass 2-3 kg, range 2-5 km, low power) for low cost civil/military reconnaissance
- Payload: Optical instrument for real/near real time imaging
- Activities:
  - Sizing of micro UAV
  - Design of RF link (laptop based)
  - Design of imager electronics
- Design drivers: Low cost (< $1000), simplicity, ease of use
- Applications: Forest fire reconnaissance, refugee/border monitoring, military battle field reconnaissance
10 Conclusion

- CMGs can be an attractive, efficient, novel, alternative ACS systems for agile Small Satellites
- Proven that CMGs are viable for agile small satellites and can potentially make them more efficient, profitable and versatile platforms than before
- BILSAT CMGs will be the first commercial CMGs in the world to fly in space, perform actual mission tasks (stereo-imaging)
- Exciting research topics in controls (space, aeronautics)
- Collaborate with METU-Aerospace
- Surrey offers MSc, PhD in aerospace/satellite engineering
Questions ?