Design Considerations for Miniaturized Control Moment Gyroscopes for Rapid Retargeting and Precision Pointing of Small Satellites

Small Satellite Conference
August 2-7, 2013, Logan, Utah

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Motivation

- With miniaturization and advances in electronics, there is a significant interest in small satellites.

- There is interest in utilizing commercial off-the-shelf (COTS) components in the pico-/nano-satellite community.

- A COTS based ACS capable of rapid reorientation (i.e. high torque) and precision pointing (i.e. high torque precision) can improve mission utility of small satellites.

- An analysis of COTS hardware indicates a CMG-RW hybrid approach is suitable for small satellites.

- A CMG-RW Hybrid approach utilizes torque amplification of CMGs in the rapid retargeting mode and direct torque capability of flywheel motors in precision pointing mode.
System details

Satellite

- 12 U size
- 20 kg mass
- 18 W average on orbit power

ACS

- 4 Hybrid CMGs in pyramidal configuration
- Pyramid angle = 54.74 degrees
- The CMG size, mass and power consumption is constrained by the satellite.
Satellite slew and pointing requirements

<table>
<thead>
<tr>
<th>Imaging Type</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip imaging</td>
<td>Orbit altitude ($alt$) 350 to 700 km, Slew rate 15 deg/s, Spatial resolution ($w$) 25 to 75 m, Angular resolution ($\psi$) $\psi \approx \frac{w}{alt}$, 7 to 45 arc sec</td>
</tr>
<tr>
<td>Stereoscopic imaging</td>
<td></td>
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<tr>
<td>Spot imaging</td>
<td></td>
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<tr>
<td>Area imaging</td>
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</table>
Torque accuracy assessment

- In the CMG mode, there are three parameters: gimbal speed, flywheel orientation and flywheel speed, which affect the control torque.

- In the RW mode, there are two parameters: flywheel acceleration and flywheel orientation, which affect the control torque.

- Appropriate gimbal and flywheel motors are selected based on the mass/volume/power constraints and simulations are performed to evaluate the effect of these errors on the output torque.

<table>
<thead>
<tr>
<th>Satellite inertia</th>
<th>$\begin{bmatrix} 0.21 &amp; 0 &amp; 0 \ 0 &amp; 0.21 &amp; 0 \ 0 &amp; 0 &amp; 0.3 \end{bmatrix}$</th>
<th>kg·m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flywheel inertia</td>
<td>$32 \times 10^{-6}$</td>
<td>kg·m²</td>
</tr>
<tr>
<td>Flywheel speed</td>
<td>12000</td>
<td>RPM</td>
</tr>
</tbody>
</table>
Effect of flywheel speed variation

- The flywheel speed error is assumed to follow a normal distribution with 2-sigma limit of 12 RPM.
- This error produces highest torque disturbance compared to other error sources.
- However, it occurs at flywheel speed (200 Hz) and can be filtered with appropriate damping.
Effect of gimbal speed/position inaccuracy

- Gimbal speed is assumed to follow a normal distribution with 2-sigma limit of 0.05 deg/s; corresponding error in gimbal position knowledge is 0.01 degrees.
Effect of gimbal dead zone

- Gimbal speeds slower than 0.25 deg/s are difficult to achieve with COTS components due to stiction. This makes torques smaller than 0.1 mNm unachievable.
Effect of flywheel acceleration error

- Flywheel acceleration error can be controlled within 10% of the commanded acceleration

- At small accelerations, which are expected during hybrid mode, the contribution of this error is lowest
Hybrid-mode considerations

- When only RW based attitude control is used, the orientations of the wheels are predetermined and fixed such that torque along any desired direction can be commanded.

- In the hybrid mode, the control strategy switches from CMG to RW mode at the end of rapid slew to provide precision tracking performance.

- There is a possibility of a singular flywheel orientation. That is, the torque produced by the flywheel motors is limited to a plane and control authority in the RW mode is lost.

- Implementation of hybrid mode requires modifications to the existing CMG control laws to avoid singular flywheel orientations.

- A RW singularity parameter is defined and it is used to steer the gimbals away from RW singularities through null motion.
New steering law – Hybrid mode

- The steering algorithm under consideration is a combination of a GSR (Generalized Singularity Robust) steering law and null motion.

- The torque is mapped to the gimbal speeds and flywheel acceleration as follows:

\[
\dot{\delta} = \alpha(I_w \hat{\Omega})^{-1}[A^T(AA^T + \lambda E)^{-1}\tau + \beta d]
\]

\[
\dot{\Omega} = (1 - \alpha)I_w^{-1}B^T(BB^T)^{-1}\tau
\]

- \(A\) and \(B\) are projection matrices for gyroscopic and direct torques. \(d\) is the null vector, and \(\alpha\) is the mode switch parameter, which is externally selected.

- \(\lambda\) introduces torque error to steer the gimbals away from a CMG singularity and \(\beta\) adds null motion to steer the gimbals away from a RW singularity. They are defined as follows:

\[
\lambda = \lambda_0 \exp(-\mu_1 \det(AA^T)), \quad \beta = \beta_0 \exp(-\mu_2 \det(BB^T))
\]
Results

- Simulations consist of a rest-to-rest rapid retargeting and precision pointing (R2P2) maneuver.

- The satellite is commanded to reorient by 30 degrees. The initial direction of the sensor boresight vector is $[1,0,0]^T$ and final direction is $[\cos(-30), \sin(-30), 0]^T$.

- Simulations incorporate flywheel acceleration errors and gimbal speed/position errors.

- Transition from CMG to RW mode occurs between 100 and 110 seconds by changing the value of $\alpha$ from 1 to 0.

- The pointing performance of the hybrid steering law is compared with the CMG only GSR steering law.
Results

GSR inverse

Hybrid steering logic

Quaternion error

Quaternion error

Quaternion error – steady state region

Quaternion error – steady state region

Mode transition
Results

GSR inverse

Hybrid steering logic

Sensor boresight vector projection

Sensor boresight vector projection

Mode transition
Results

- High torque motors are not required since flywheel speed variations in the RW mode are limited to a few RPMs. Thus, high torque motors are not needed.
Conclusion and Future Work

- An ACS suitable for satellites in the 15-20 kg mass range is discussed in this paper with consideration of the size, weight, and power limitations imposed by the satellite.

- An analysis was performed to study the torque errors associated with commercially available (COTS) gimbal and flywheel motors selected to meet the satellite imposed limitations as well as the mission requirements.

- A hybrid steering logic, which uses gyroscopic torque for rapid retargeting and direct torque of flywheel motors for precision pointing, was introduced and was shown through simulations to be a practical solution for rapid retargeting and precision pointing of small satellites using COTS components.

- Future work involves prototyping and experimental testing of this system. Additionally, momentum management strategies will be developed to minimize flywheel speed drifts that may occur after multiple maneuvers.
Acknowledgement

- The research is supported by NASA Grant # NNX13AR49A, “An Integrated Precision Attitude Determination and Control System” in partnership with NASA Langley Research Center.
Questions?