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

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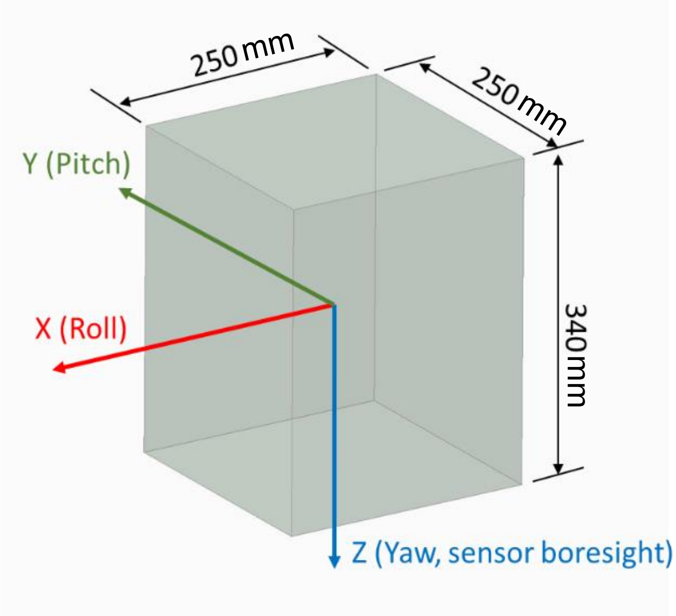
Motivation

- 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

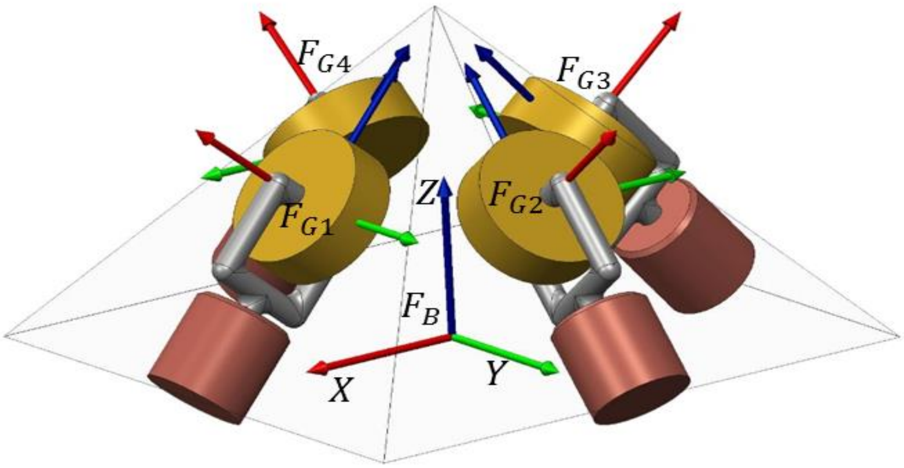
Satellite

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

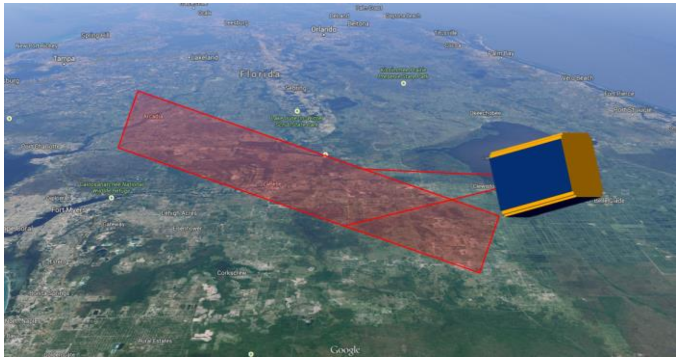


ACS

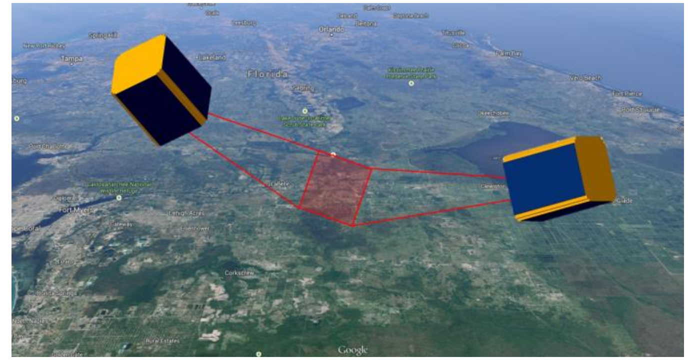
- 4 Hybrid CMGs in pyramidal configuration
- Pyramid angle = 54.74 degrees
- The CMG size, mass and power consumption is constrained by the satellite.



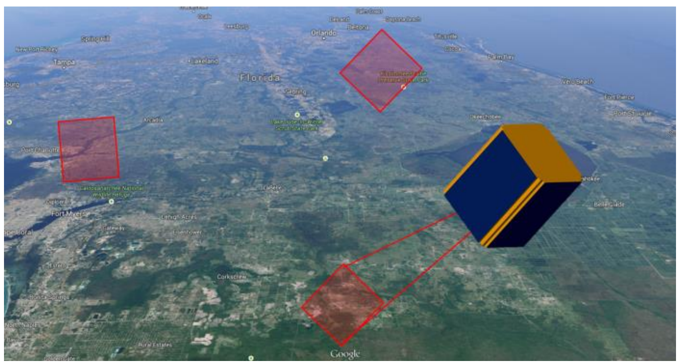
Satellite slew and pointing requirements



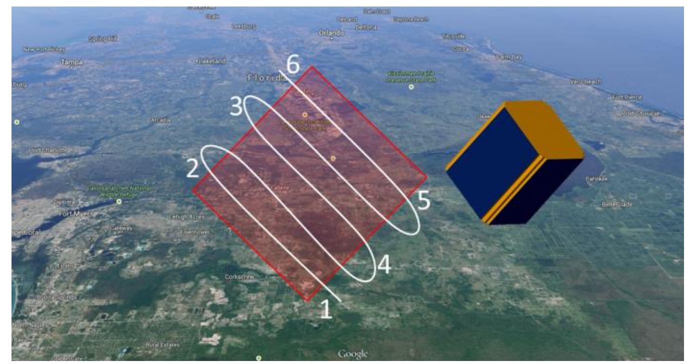
Strip imaging



Stereoscopic imaging



Spot imaging



Area imaging

Orbit altitude (alt)	350 to 700 km
Slew rate	15 deg/s
Spatial resolution (w)	25 to 75 m
Angular resolution (ψ)	$\psi \cong \frac{w}{alt}$, 7 to 45 arc sec

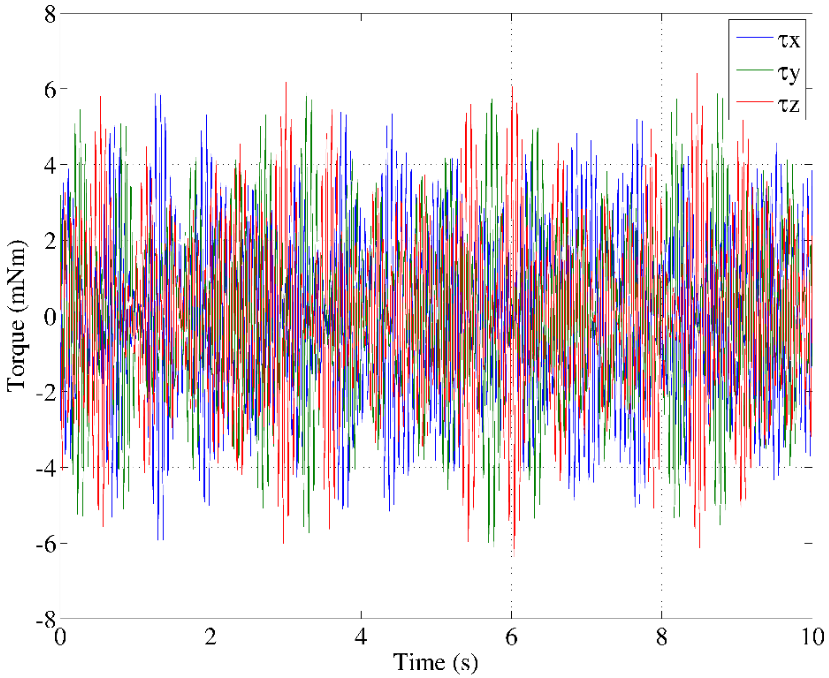
Torque accuracy assessment

- 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.

Satellite inertia	$\begin{bmatrix} 0.21 & 0 & 0 \\ 0 & 0.21 & 0 \\ 0 & 0 & 0.3 \end{bmatrix}$	kg·m^2
Flywheel inertia	32×10^{-6}	kg·m^2
Flywheel speed	12000	RPM

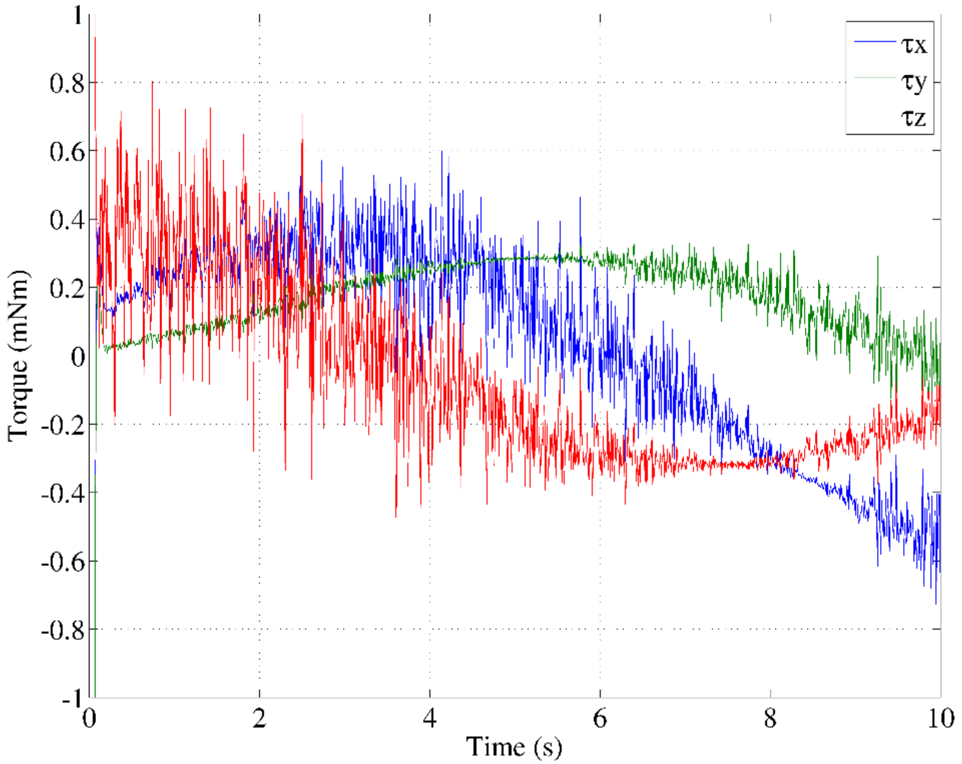
Effect of flywheel speed variation

- 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.



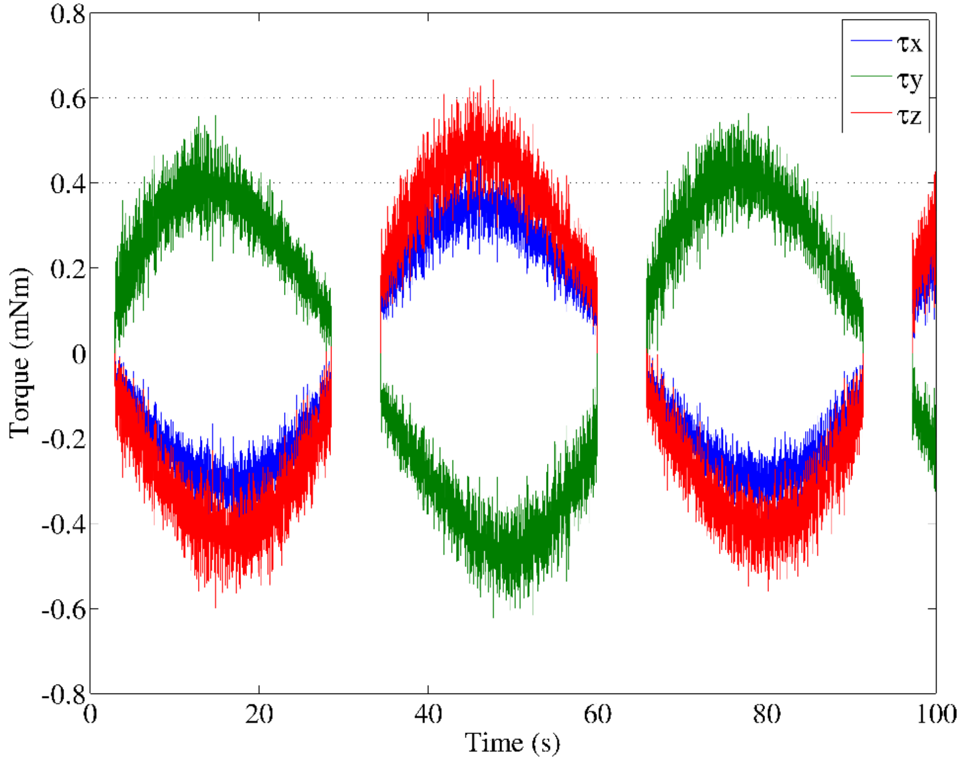
Effect of gimbal speed/position inaccuracy

- 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



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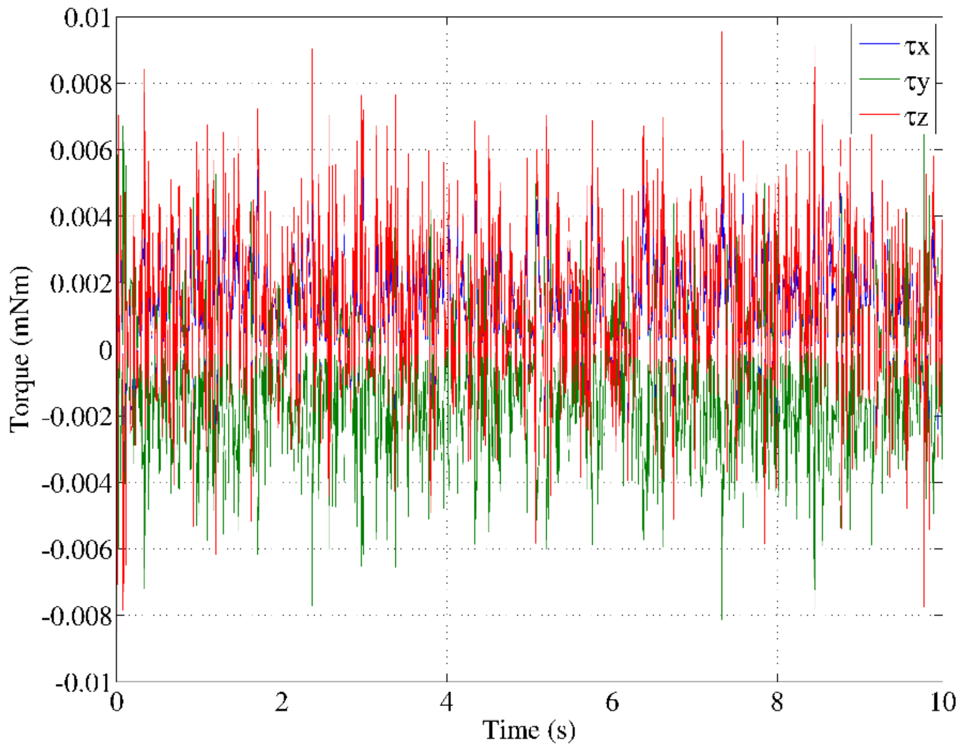
Effect of flywheel acceleration error

- 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

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

$$\dot{\boldsymbol{\Omega}} = (1-\alpha)I_w^{-1}\boldsymbol{B}^T(\boldsymbol{B}\boldsymbol{B}^T)^{-1}\boldsymbol{\tau}$$

- $\boldsymbol{A}$ and $\boldsymbol{B}$ are projection matrices for gyroscopic and direct torques. $\boldsymbol{d}$ is the null vector, and α is the mode switch parameter, which is externally selected.

- λ introduces torque error to steer the gimbals away from a CMG singularity and β adds null motion to steer the gimbals away from a RW singularity. They are defined as follows

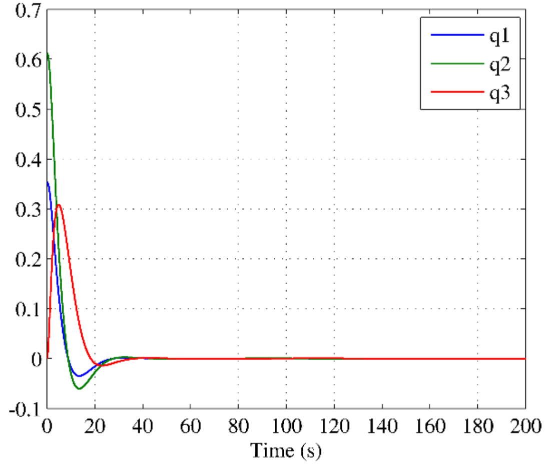
$$\lambda = \lambda_0 \exp(-\mu_1 det(\boldsymbol{A}\boldsymbol{A}^T)), \qquad \beta = \beta_0 \exp(-\mu_2 det(\boldsymbol{B}\boldsymbol{B}^T))$$

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 α from 1 to 0.
- The pointing performance of the hybrid steering law is compared with the CMG only GSR steering law.

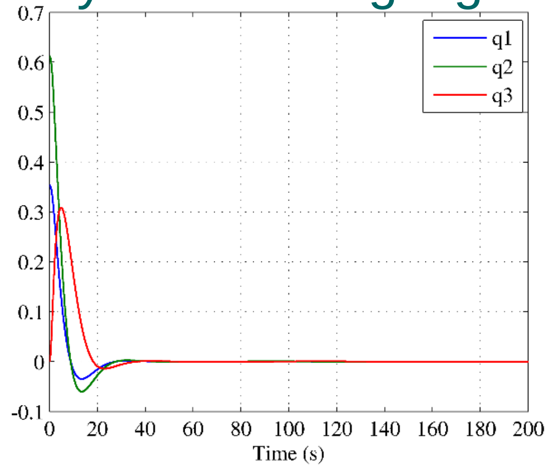
Results

GSR inverse

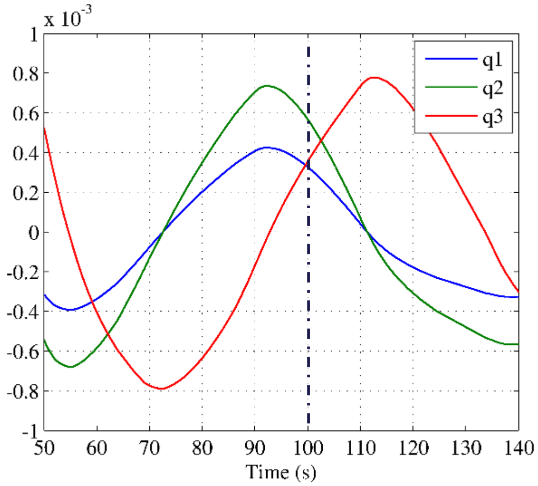


Quaternion error

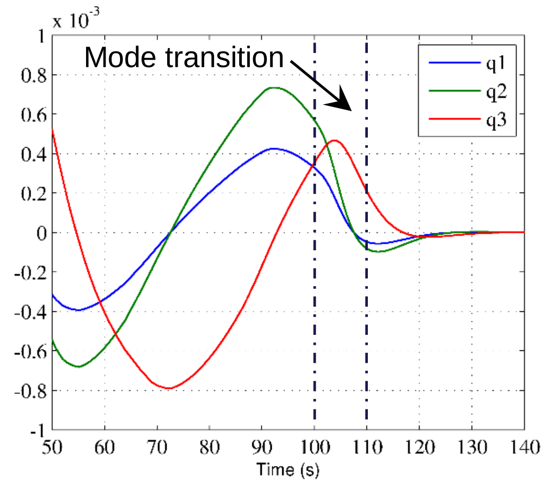
Hybrid steering logic



Quaternion error



Quaternion error – steady state region



Quaternion error – steady state region

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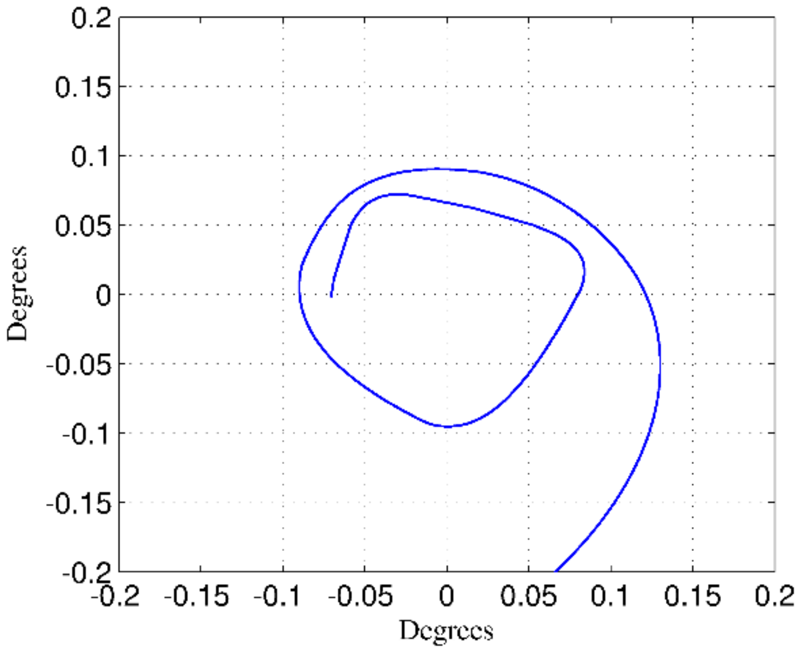
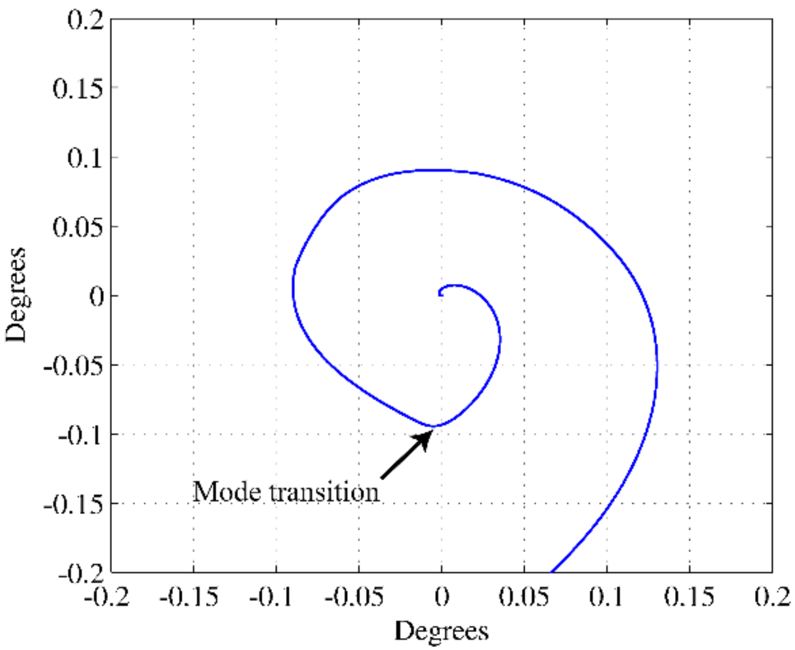
GSR inverse



Sensor boresight vector projection

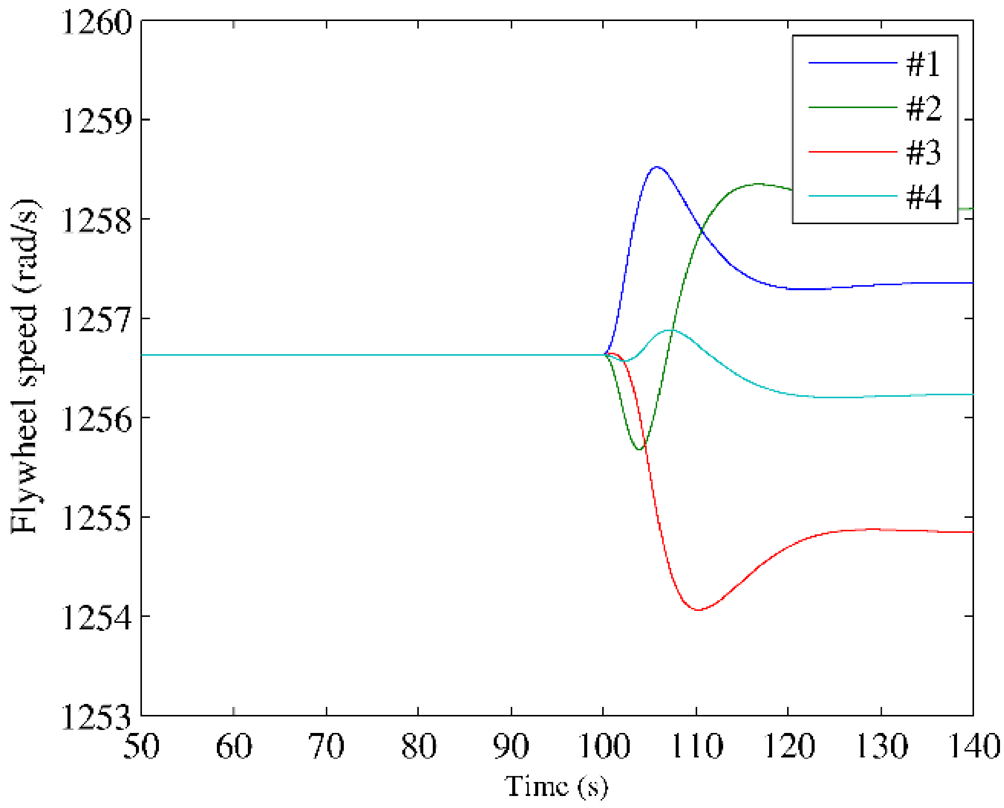
Hybrid steering logic



Sensor boresight vector projection

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.



Flywheel speed in hybrid mode

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

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Questions?