Control of a Thrust-Vectoring CubeSat Using a Single Variable-Speed Control Moment Gyroscope

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Image Credit: Michigan Aerospace Manufacturers Association

Objective

- CubeSats should be as small, light, cheap, and simple as possible
  → we want to minimize the amount of thrusters and MEDs per CubeSat
- Full attitude control is impossible with just one MED and one thruster
  - Need at least 3 reaction wheels or CMGs for 6-axis control
  - Using 4 to 6 MEDs is common for redundancy

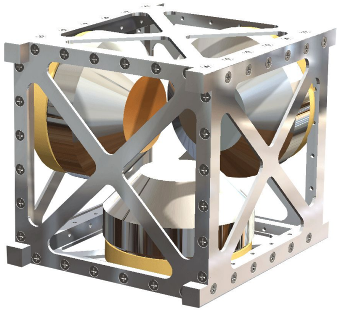


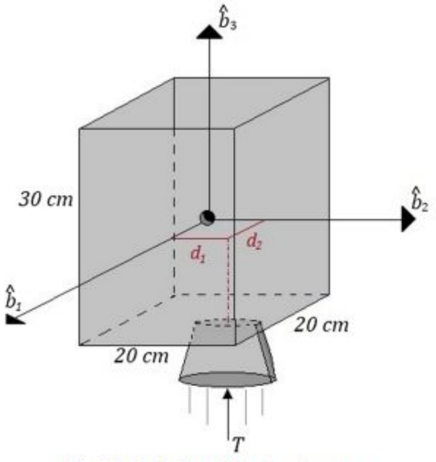
Image Credit: Schweber, Bill. “Reaction wheels ensure satellites maintain the right attitude: Part 1”, Microcontroller Tips, microcontrollertips.com

Objective

- What if we only need to point one axis of the CubeSat in a certain direction, but don’t care about MED redundancy or spinning around that axis?
  - Fine for orbital maneuvers
  - Not fine for sensors that need to be stabilized in all three axes
- Then we can use a VSCMG for attitude control and a thruster for translations
  - This is the minimum number of actuators needed for orbital maneuvers
- Configuration is valid if some control law reaches stability in torque-free motion
- Additional objectives:
  - Show that the system is robust by maintaining stability with perturbations and thruster offset
  - Apply the control law to a rendezvous mission

Dynamic Theory

- Assumptions
  - Negligible Gimbal acceleration
  - Time-varying spin rate
  - $m_{cmg} << m_{SC}$ $\therefore$ $\boldsymbol{J}$ is constant
- Dynamics of problem defined as $\dot{\omega} = J^{-1}(-\omega^x J\omega + u + d)$
- where the control term $u = -I_{ws}\dot{\Omega}\hat{s} - I_{ws}\Omega\dot{\gamma}\hat{t}$
- and the secondary term $d = -I_{cg}\dot{\gamma}\omega^x\hat{g} - I_{ws}\Omega\omega^x\hat{s}$
- and *m* represents any disturbance torques on the spacecraft, which are only considered for the offset thruster case where $m = [\|\boldsymbol{T}\|d_1 \;\; \|\boldsymbol{T}\|d_2 \;\; 0]$

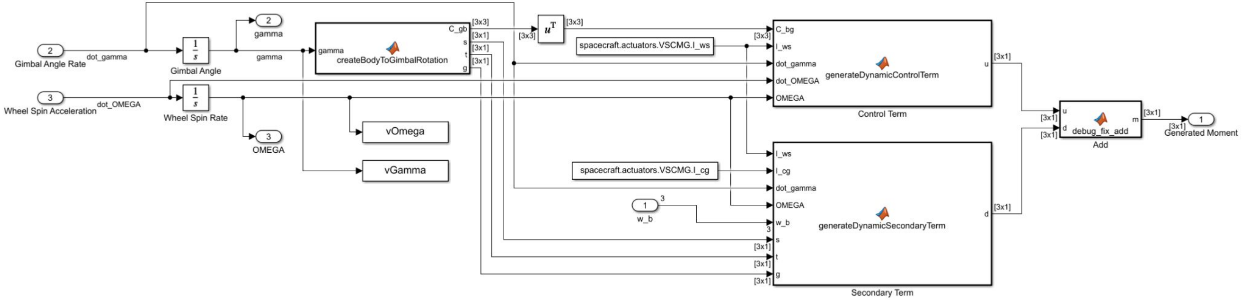


Stability Analysis

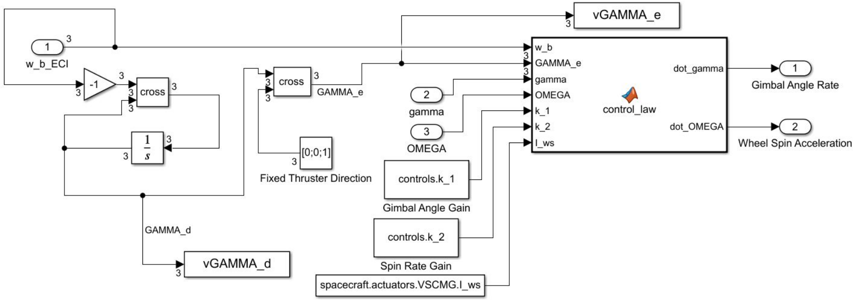
- Nonlinear Reduced-Attitude Control for Thrust-Vectoring
  - Asymptotically stable for states ω_1 and ω_2 while ω_3 stabilizes to a constant value.
- Nonlinear Control for Impulsive Thrust Vectoring
  - Asymptotically stable for states ω_1, ω_2 and the pointing error $\mathbf{\Gamma}_e$. While ω_3 is not guaranteed to converge to zero, pointing direction is invariant to changes in ω_3
- Nonlinear Tracking for Low-Thrust (Continuous) Vectoring
  - Asymptotically stable for the states ω_e* and $\mathbf{\Gamma}_e$
  - ω_{e3} does not converge to a constant value

Implementation

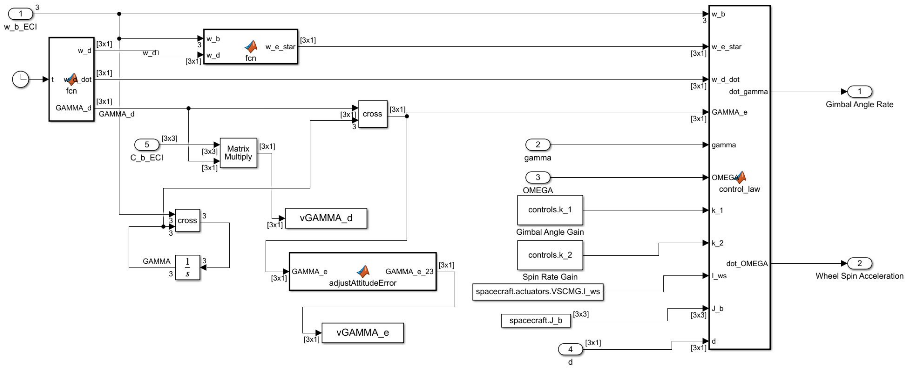
VSCMG



Repointing



Tracking



Simulation Parameters

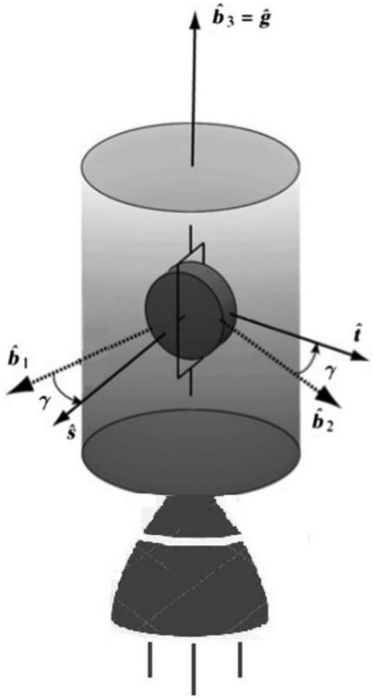


Fig. 2 System configuration.

J_b	$\begin{bmatrix} 1.009 & 0 & 0 \\ 0 & 0.251 & 0 \\ 0 & 0 & 0.916 \end{bmatrix}$	kg·m^2
I_{ws}	0.002	kg·m^2
I_{cg}	0.03	kg·m^2
Ω_0	1	rad/s
γ_0	1	rad
ω_0	$\begin{bmatrix} 0 \\ 0 \\ 0.15 \end{bmatrix}$	rad/s

Repointing

$$[\Gamma_{d0}]^B \begin{bmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \end{bmatrix}$$

k_1	0.5
k_2	0.5

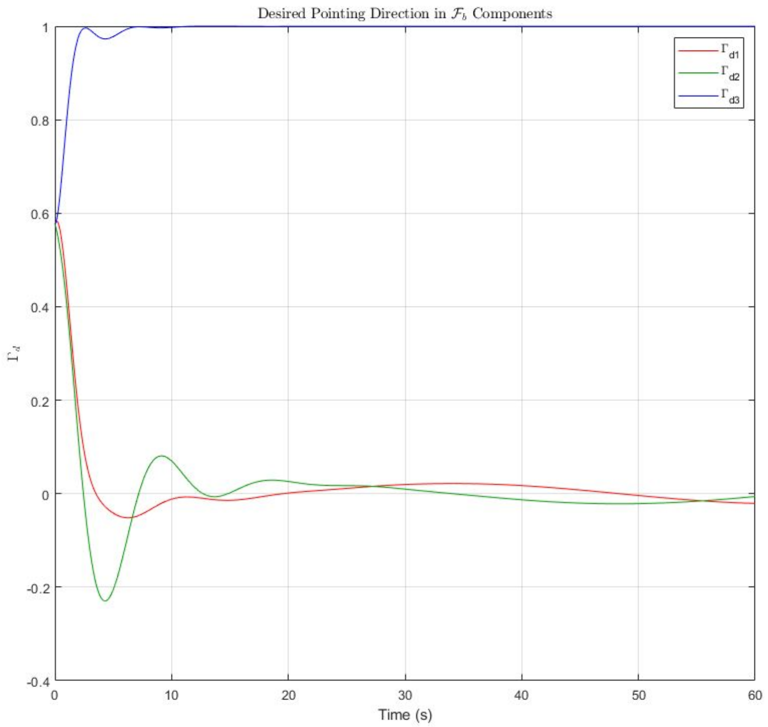
Tracking

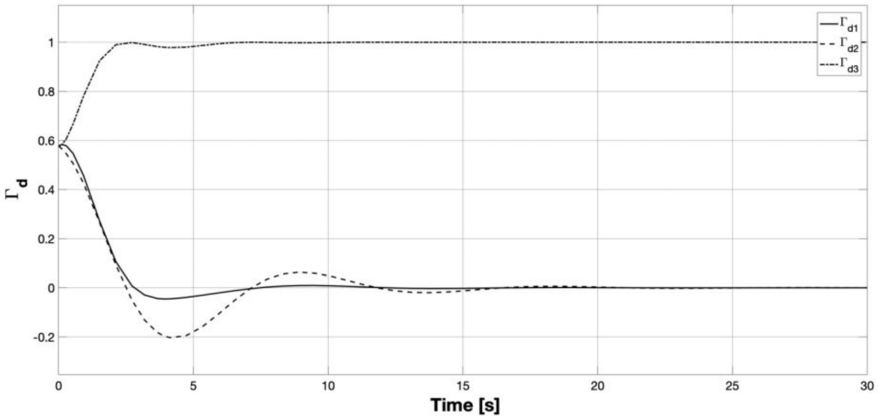
$$[\Gamma_{d0}]^N \begin{bmatrix} 0 \\ \sin(0.2t) \\ \cos(0.2t) \end{bmatrix}$$

k_1	0.1
k_2	0.1

Image Credit: [1]

Repointing Simulation Results





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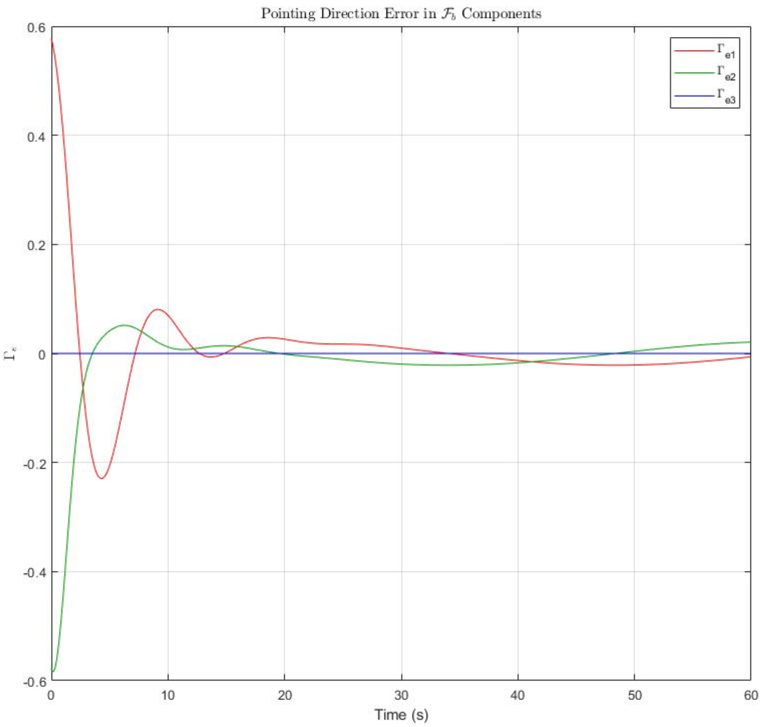

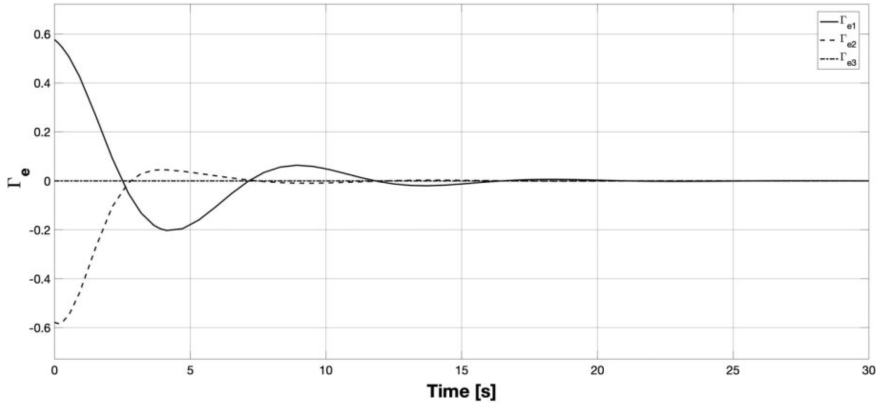

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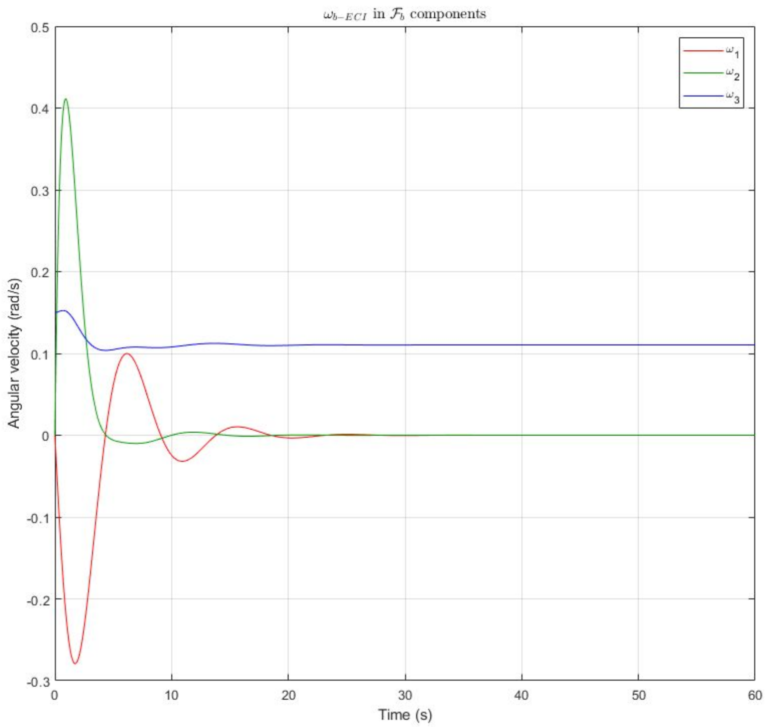

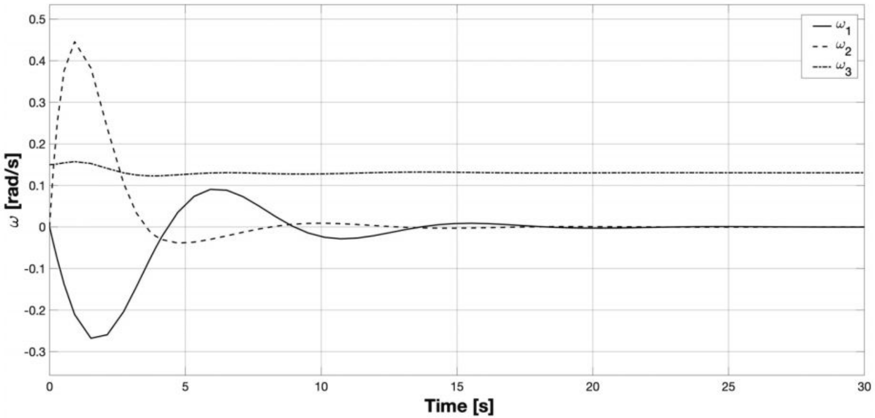

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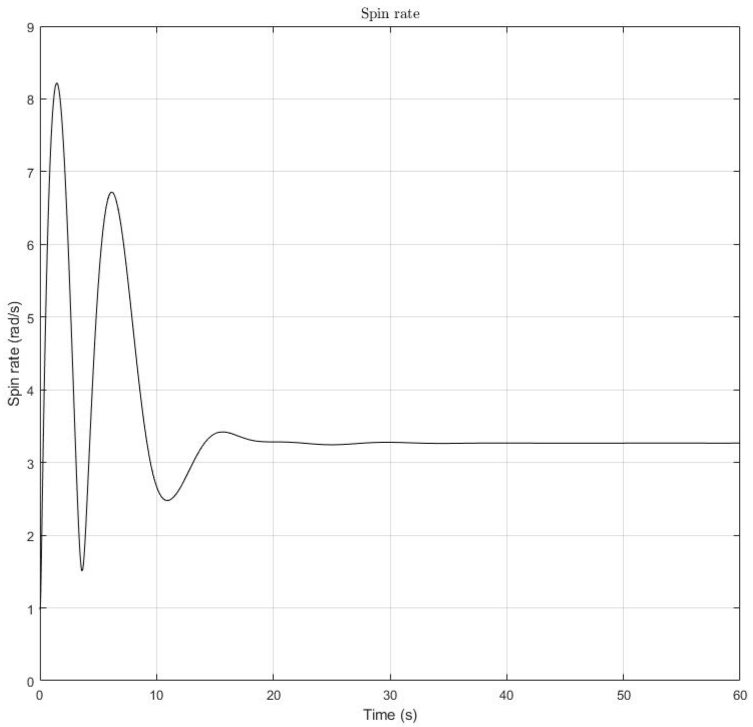

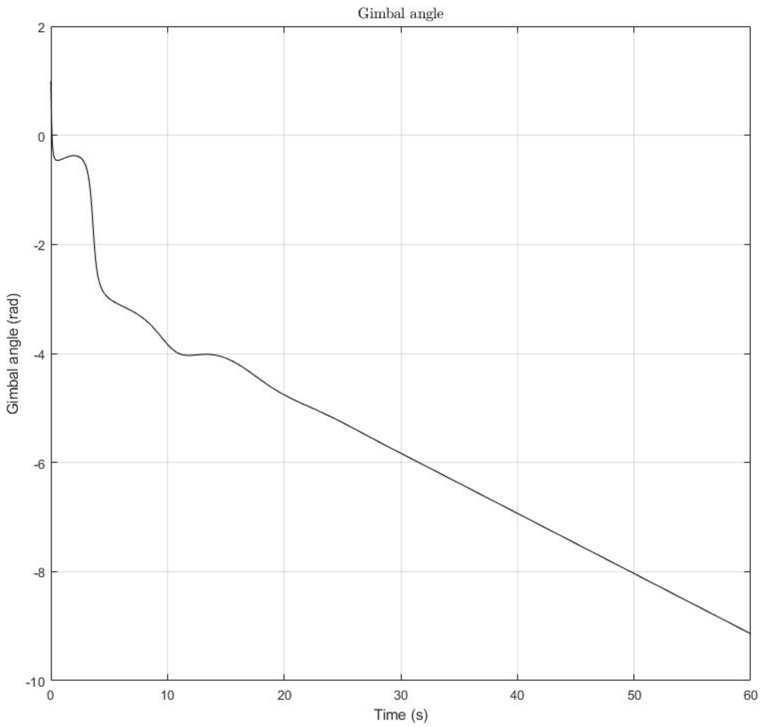

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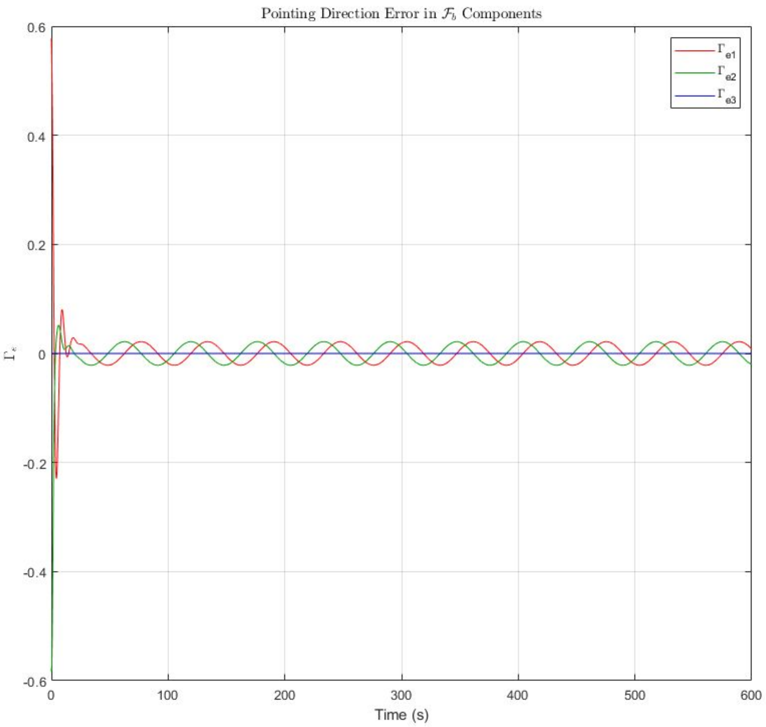
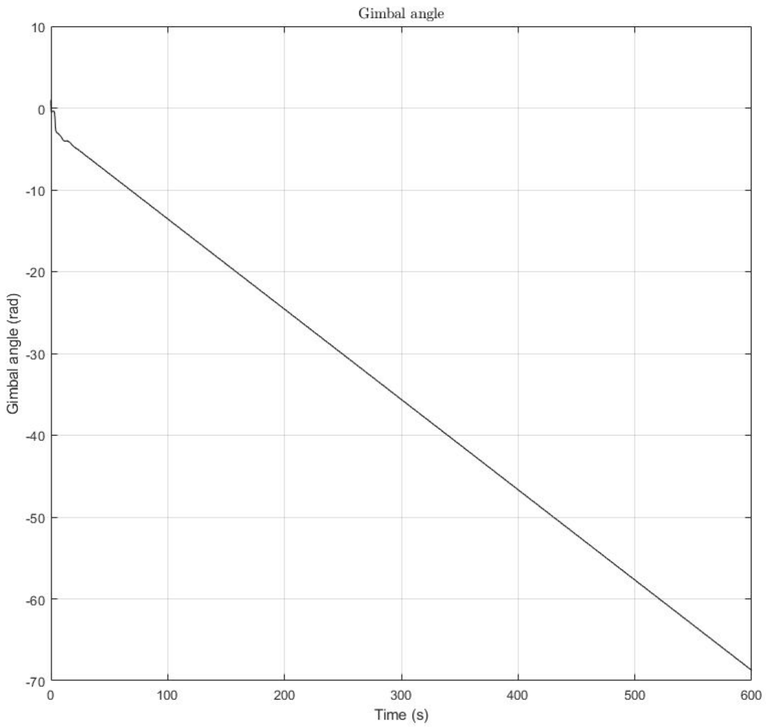
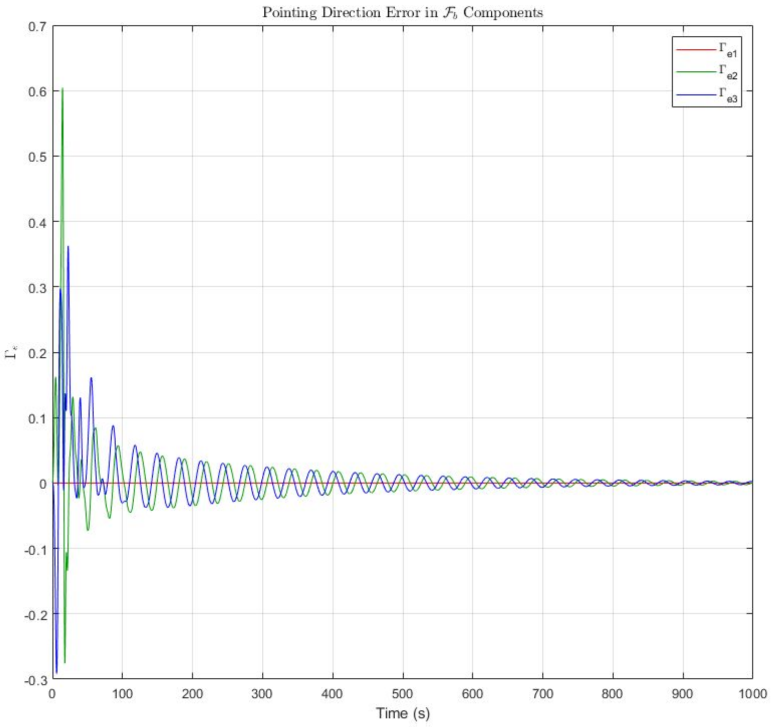
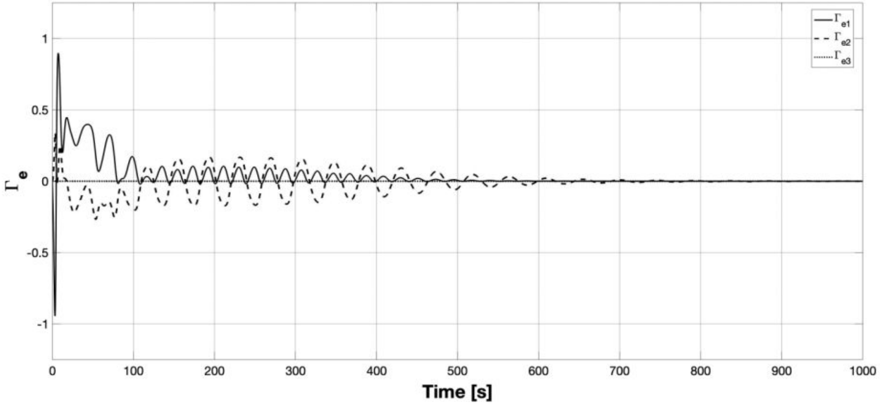




Tracking Simulation Results





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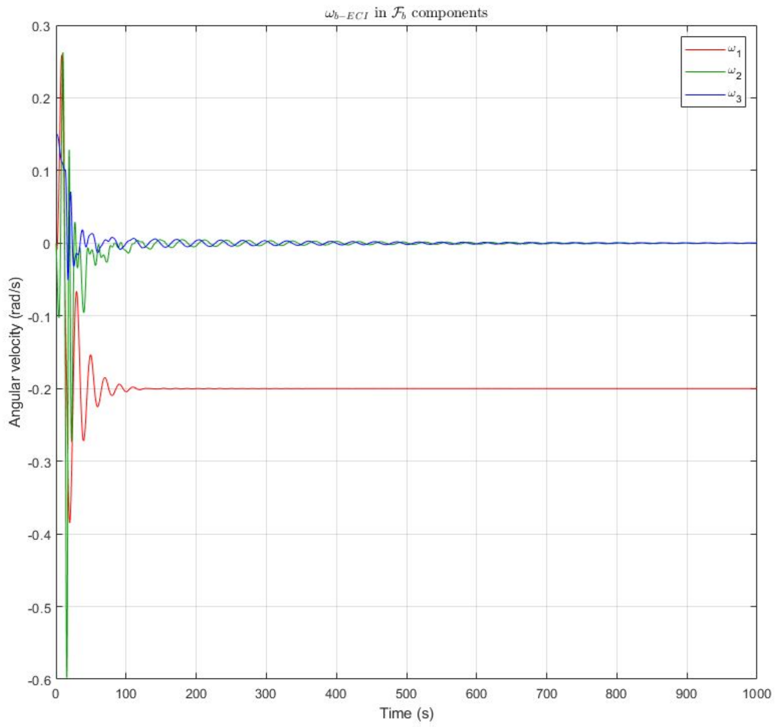

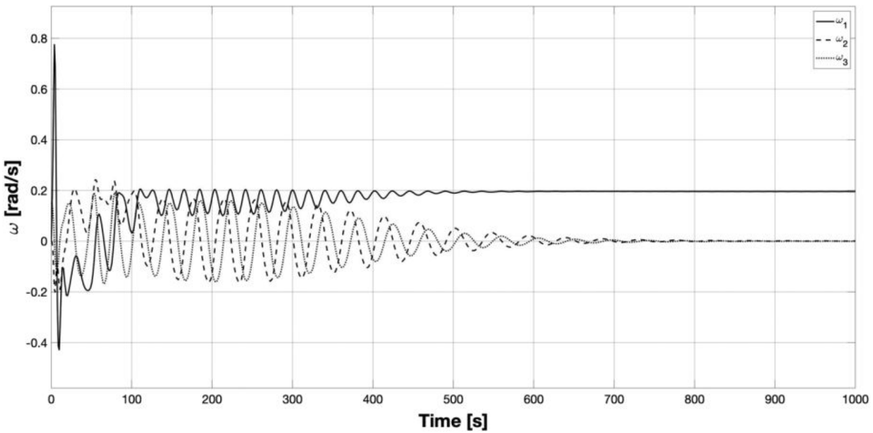

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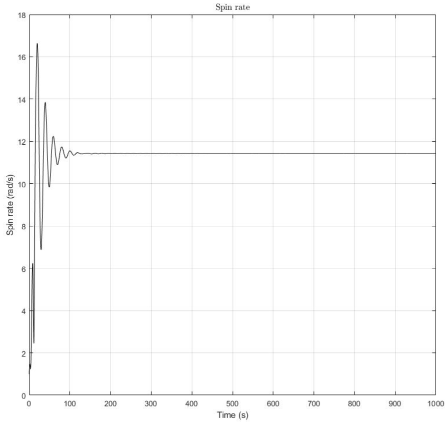
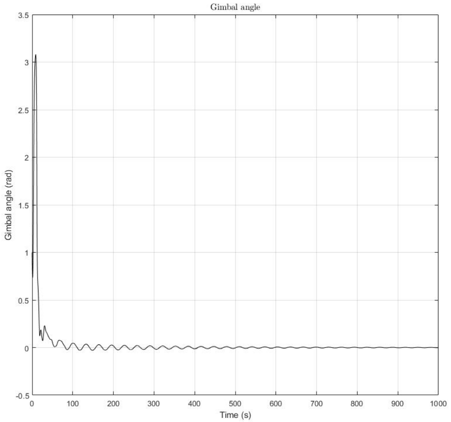
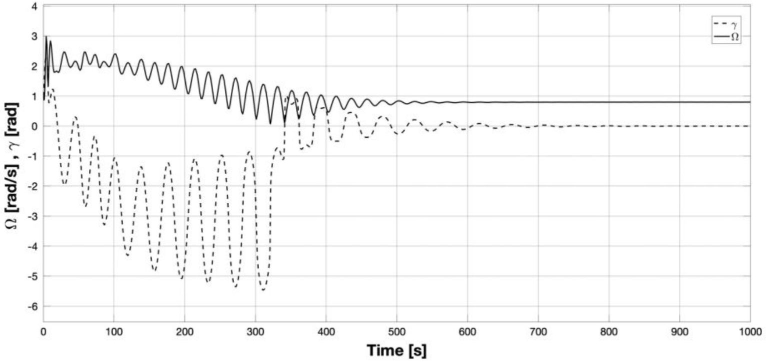
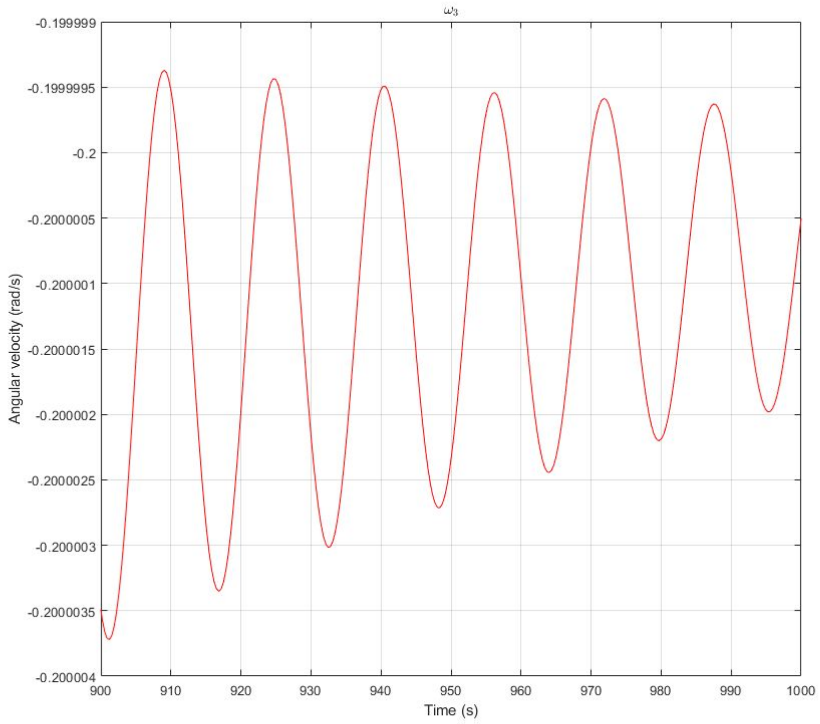
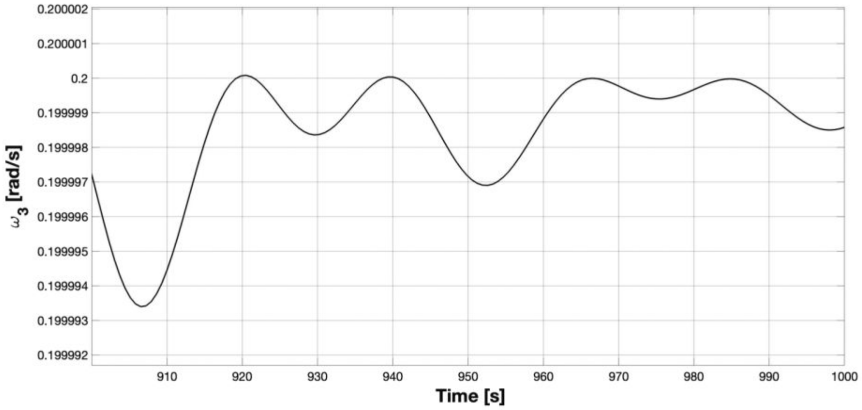






Tracking Simulation Results (steady state)





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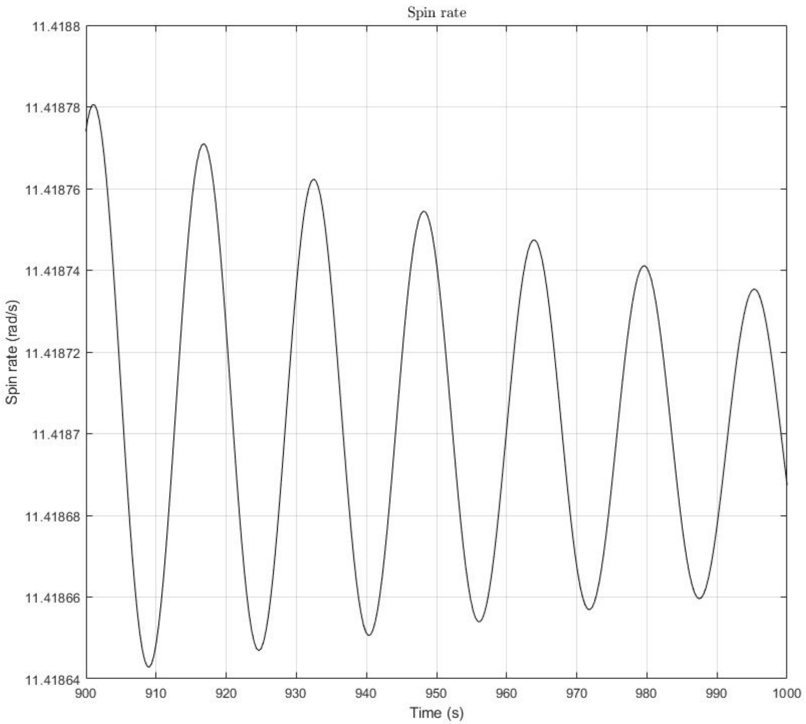

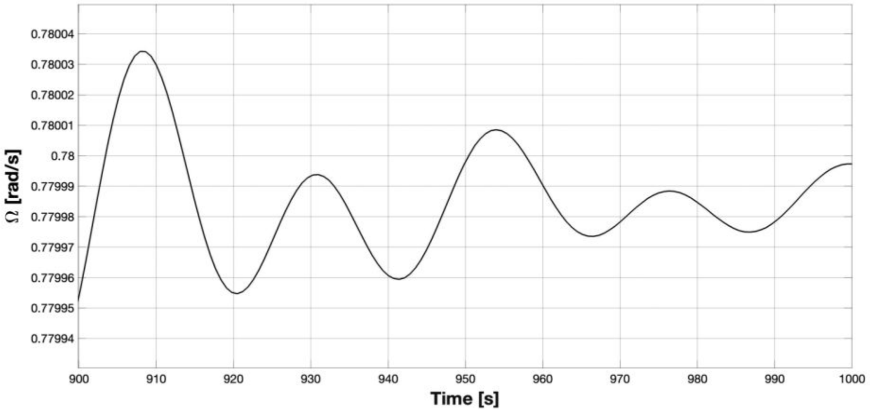

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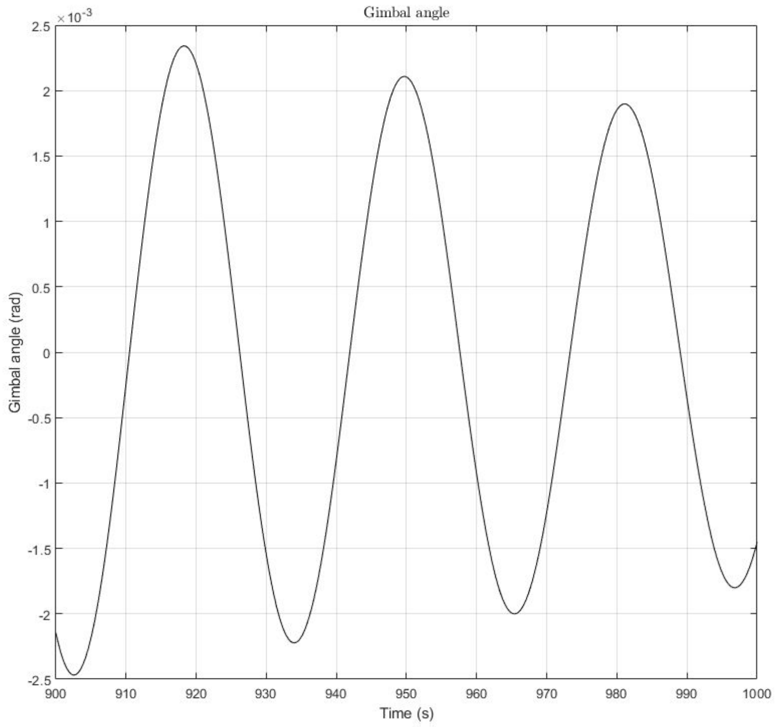

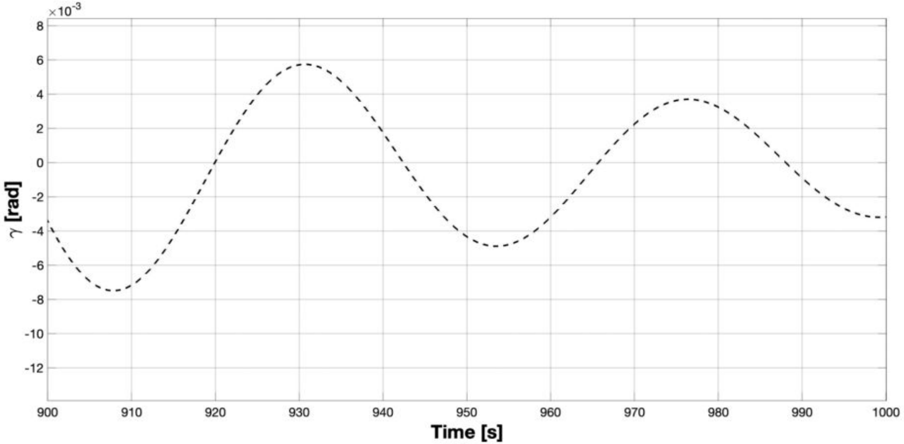

Conclusion

- Not recommended to rely solely on the VSCMG for attitude control
  - Redundancy (or lack thereof)
  - Complexity
  - Settling time
  - Only 2/3 axes controlled
- Instead, use the VSCMG as a backup for other MEDs
  - Maintain pointing even with total failure of all other MEDs
- Future work
  - Rendezvous simulation
  - Offset thruster simulation
  - Implementation of external disturbances

References

[1] Control of a Thrust-Vectoring CubeSat Using a Single Variable-Speed Control Moment Gyroscope

James D. Biggs and Gaetano Livornese

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