Gravity Probe B Gyroscope Electrostatic Suspension System (GSS)

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Abstract

Gravity Probe B developed a hybrid digital/analog electrostatic suspension control system for the experiment's science gyroscopes. This system operates over 8 orders of force magnitude while minimizing classical torques on the gyroscope. An adaptive LQE digital control algorithm was developed to meet the high dynamic range requirements, while minimizing suspension-induced torques. A set of three backup, all-analog proportional-derivative (PD) controllers maintain rotor centering in the event of computer faults during all phases of the mission. The capacitive position sensing system measured rotor position to a noise floor of 0.15 nm/√Hz in the science band (5 - 30 mHz). This system also applied controlled torques to perform a post spin-up alignment of the gyroscope spin axes to within 10 arc-sec of a desired orientation. The GSS contributed to drag-free operation of the space vehicle by using one of the gyroscopes as an isolated, inertial proof mass and was able to resolve accelerations to the 10^{-12} g level.

Design Drivers

Minimize Torques

"Do Nothing"

- Slow response/bandwidth
- Low suspension voltages
- SQUID compatible – low EMI.
- Science-tuned controller.
- "Zero force" drag free control.

Protect the Rotor

"DO NOT let the rotor crash"

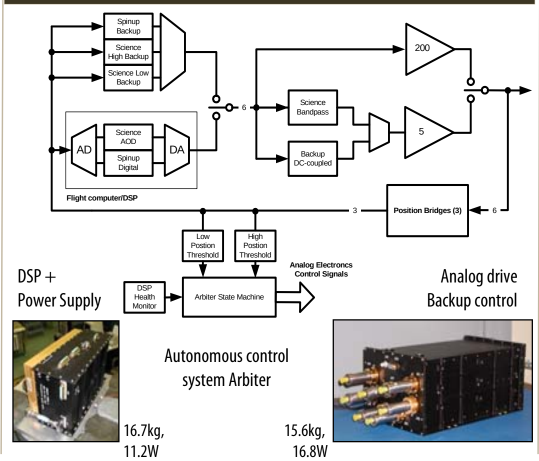
- Fast response/bandwidth.
- High suspension voltages.
- High position bridge SNR
- Robust control algorithm.
- Ground test and spinup control.

Spaceflight compatible

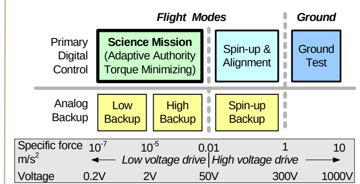
- Implement with slow computing resources and electronics.
- Endure vibration, shock, radiation, thermal, vacuum environment
- Operate semi-autonomously with low drift and tight power budget.

Many conflicting requirements makes for a challenging design!

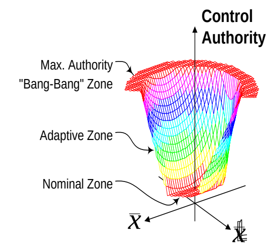
Controller Architecture

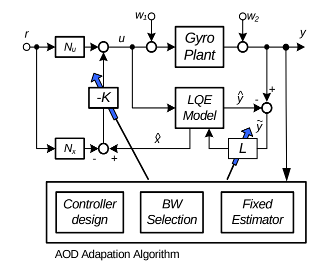


Control Algorithm



- Primary mode: DSP torque minimizing LQG control loop.
- Backup controllers: Robust all-analog fixed BW – 3 types.
- Control spans pans 8 orders of force magnitude (1g to 10ng)



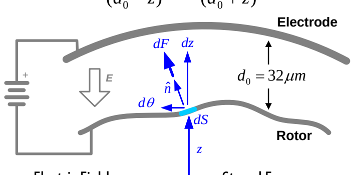


Electrostatic Forces and Torques

Plant Characteristics:

- Open-loop unstable, Nonlinear
- Multi-input/Multi-output
- Torques and forces a function of applied voltages

$$F_z = K\left(\frac{(V_{z1}-V_r)^2}{(d_0-z)^2} - \frac{(V_{z2}-V_r)^2}{(d_0+z)^2}\right)$$



Electric Field:

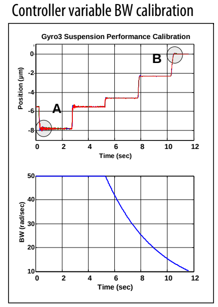
$$\mathbf{F} = -\frac{\partial}{\partial\rho}\left[\tfrac{1}{2}CV^2\right] \qquad \tau = -\frac{\partial}{\partial\eta}\left[\tfrac{1}{2}CV^2\right]$$

Stored Energy:

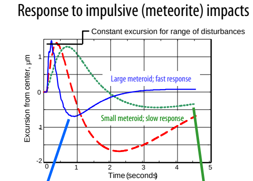
$$\mathbf{F} = \frac{\varepsilon_0}{2}\iint_S |\mathbf{E}|^2\,\hat{\mathbf{n}}\;dS \qquad \tau = \frac{\varepsilon_0}{2}\iint_S |\mathbf{E}|^2\,(\mathbf{r}\times\hat{\mathbf{n}})\;dS$$

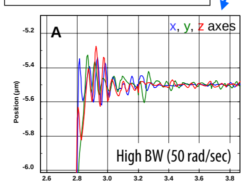
Suspension Performance

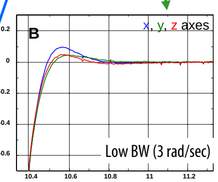
Controller variable BW calibration



Response to impulsive (meteorite) impacts

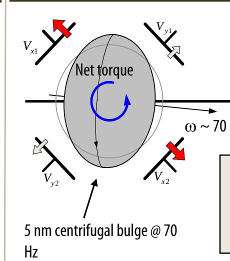






Variable bandwidth control effective at safeguarding rotor while minimizing classical torques

Spin Axis Alignment



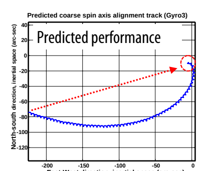
- Suspension constraints: 4

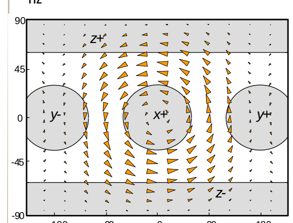
$$F_x = k\left[(V_{x1}-V_r)^2-(V_{x2}-V_r)^2\right]$$
$$F_y = k\left[(V_{y1}-V_r)^2-(V_{y2}-V_r)^2\right]$$
$$F_z = k\left[(V_{z1}-V_r)^2-(V_{z2}-V_r)^2\right]$$
$$V_r = 0 = \sum_i V_i$$

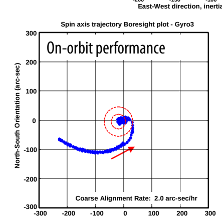
- 6 voltages ⇨ 2 open DOF in V
- Sum of voltages not constrained

$$s_x = \left[V_{x1}^2 + V_{x2}^2\right],\quad s_y = \left[V_{y1}^2 + V_{y2}^2\right]$$

Unbalancing the "common mode" pull between axes gives rise to a controllable torque against the rotor centrifugal bulge




Torque field around an electrode



Lessons and Conclusions

The Gravity Probe B Gyroscope Suspension System met its mission requirements and performed well on orbit.

1. Very high dynamic range. Operated over 8 orders of force magnitude: 1g to 10^{-8}g – Earth lab (1g), Spinup (0.1g) and science operations (10mg to 10ng).
2. Centering performance: 0.5 nm_{RMS}
3. Acceleration measurement sensitivity: 10^{-12} g for drag-free system.
4. Reliable suspension: Robust digital controller with two level analog backup control loops with independent health assessment.
5. EMI compatible with SQUID magnetometers.
6. Minimized suspension torques for science measurement to < 1 marc-sec/yr total drift ($<3\times10^{-11}$ deg/hr)
7. Maximized residual, small torques for spin axis alignment.

Suspension hardware and controls techniques useful for other spaceflight science missions: STEP, LISA.

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