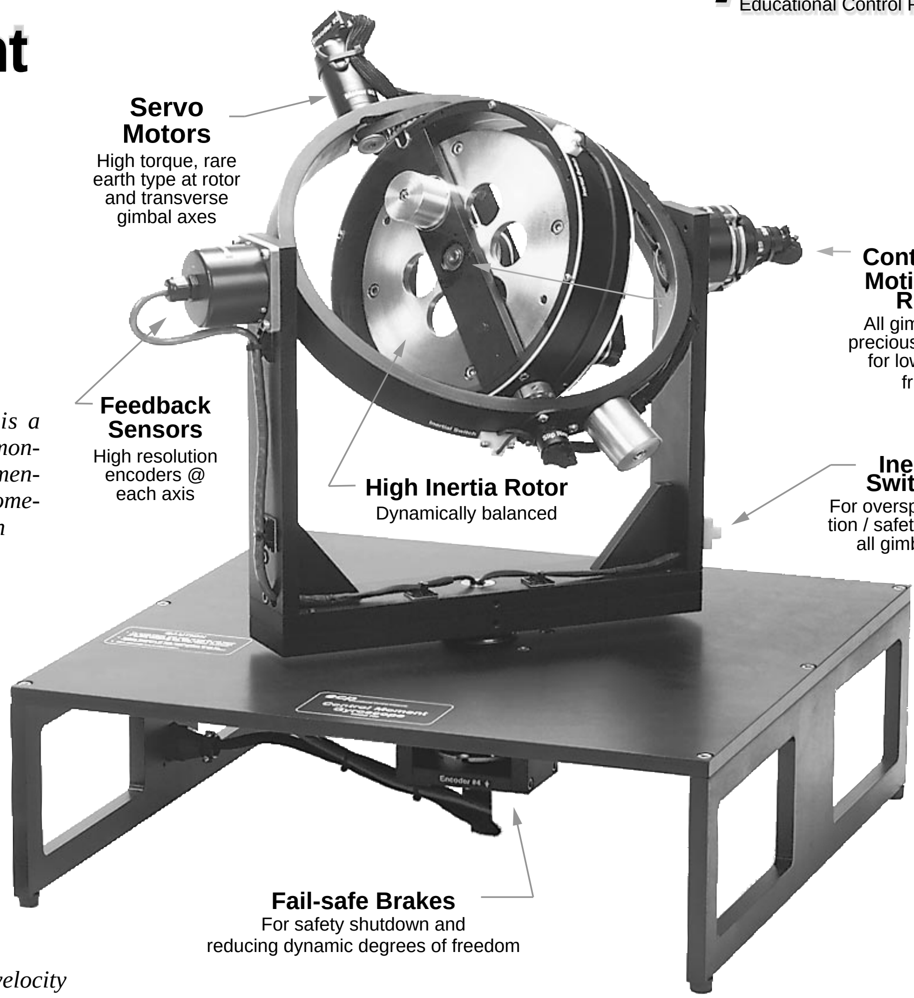
Model 750
Control Moment Gyroscope

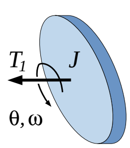
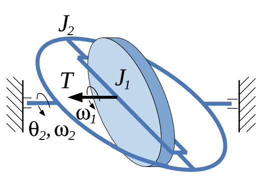
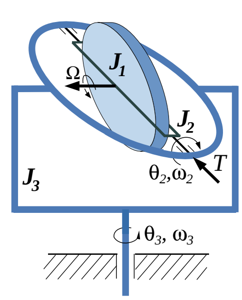
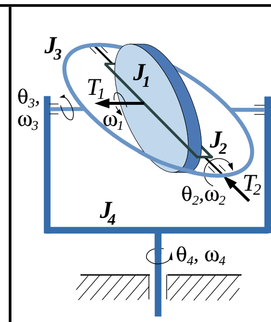
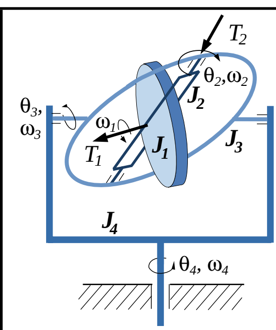
Fact Sheet

ecp
Educational Control Products



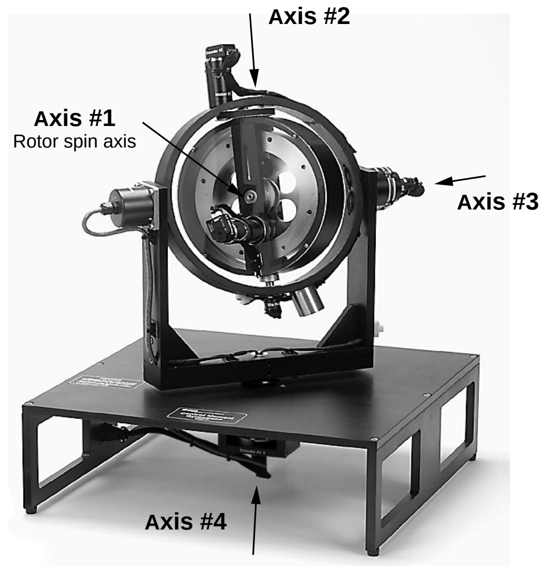
ECP's four axis Control Moment Gyroscope is a dynamically rich system that provides superb demonstrations of multi-DOF rigid body control. Elementary experiments that graphically show the phenomenon of gyroscopic torque and its use in precision high authority control are readily performed. More advanced topics range from MIMO linear control to fully general nonlinear control with singularity avoidance. Thus the system yields demonstrations that are intriguing to the layman and post-doctorate alike! In addition, the plant may be used to emulate the control of satellite attitude. Stimulating experiments first show the open loop nutation modes and then demonstrate their effective control. The apparatus includes low friction slip rings at all gimbals for unlimited range of motion, and precision encoders for feedback of all position and velocity states. A host of safety features such as fail-safe brakes, inertial rate sensing switches, and real-time watch-dog monitoring provide for safe operation of the apparatus.

A Variety Of Simple and Advanced Plant Configurations

Configuration	 **Simple Rigid Body**	 **Reaction Wheel**	 **Gyroscopic Torquer**	 **Reaction / Gyroscopic positioner (Special case)**	 **Reaction / Gyroscopic positioner (General Case)**
Equations of Motion	$J\ddot{\theta} = T$ **Brakes are applied on all axes except rotor to minimize system order**	$J_2\dot{\omega}_2 = -T$ $\omega_1 = \omega_{1_o} + \int_0^t T(\tau)/J_1\, d\tau$ **Brakes applied at second and fourth axes - see reverse page**	*For small θ_2 and symetric mass properties:* $\dot{\omega}_3 = \big(\Omega\omega_2 J_1^2 + (T_1 + (J_1^2 + 2(J_2^2 - J_1^1 - J_2^3))\omega_2\omega_3)\theta_2\big)/J_{eq}$ *where J_i^j is the jth diagonal element of $\boldsymbol{J_i}$ and* $J_{eq} = J_1^1 + J_4^3 + J_3^3 + J_2^3$ *For $\Omega >> \omega_3$,* $\dot{\omega}_3 \cong \Omega\,\omega_2 J_1^2/J_{eq}$ **Brake applied at third axis**	$\dot{\omega}_1 = \frac{J_2^2 + J_3^2 + J_4^2}{J_4^2(J_2^2 + J_3^2)} T_1$ $\dot{\omega}_2 = \frac{J_4^2\,\Omega\,\omega_4}{J_3^1 + J_4^1} + \frac{1}{J_3^1 + J_4^1} T_2$ $\dot{\omega}_3 = -\frac{1}{J_2^2 + J_3^2} T_1$ $\dot{\omega}_4 = \frac{J_4^2\,\Omega\,\omega_4}{J_4^1 + J_1^3 + J_2^3 + J_3^3}$ *Applicable to small motions in θ_2 & θ_3, arbitrarily large motions in θ_1 and θ_4, $\omega_1 \approx \Omega$ (nom. value)*	$\dot{\boldsymbol{\omega}} = \left[f(\theta_k, \omega_i, J_i^j)\right]\boldsymbol{\omega}$ $+ \left[g(\theta_k, J_i^j)\right]\boldsymbol{T}$ *where: $i = 1,2,3,4$* *$j = 1,2,3$* *$k = 2,3$* *Other notation as given at left* **Explicit expressions provided in system documentation**

Advanced System Features, Time-saving Benefits

- *High momentum, dynamically balanced rotor provides high inertial stiffness and gyroscopic authority for precision control and smooth system operation*
- *Rare earth magnet motors provide high torque density with low parasitic inertia*
- *High resolution encoders at each axis provide for precision system control and data analysis, and for low noise real-time angular rate measurement*
- *Electromechanical brakes at two axes, and servo brake at a third one let you quickly set up the system in one to four degrees of freedom and in any desired gimbal orientation*
- *Gold plated slip rings at each gimbal provide continuous rotation at all axes for unconstrained range of motion with low electrical noise and low friction.*
- *Durable plate and bar aluminum construction with high grade ball bearings and ruggedized industrial grade electronics yield highly reliable operation*
- *Step-by-step instructions, intuitive interface software, and detailed experiments with solutions assure productive use of laboratory time.*
- *Safety features such as fail-safe g-switches and brakes provide high gimbal rate detection and automatic safety shutdown. Additional features such as amplifier thermal dissipation limit, over-current shutdown, and watch-dog timer functions assure equipment durability and a safe operating environment*
- *Bench top sized with quick connect cabling for easy transportability and re-connection to rest of system*



(Axes shown in off-nominal orientation for clarity of view)

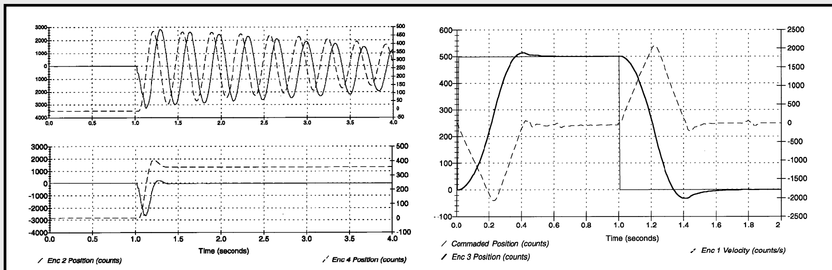
Thought-provoking Experiments

The CMG system is furnished with a broad range of experiments that graphically demonstrate important theoretical principles and applied control implementation. All experiments include detailed student procedures, supplementary exercises, and complete instructor solutions. Also provided are plant dynamic models, Matlab® scripts for analysis and simulation, and optional exercises to taylor your course content.

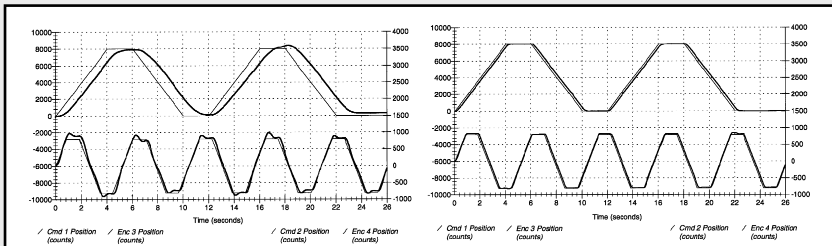
Initial tests demonstrate salient dynamic characteristics and identify plant parameters. Experiments demonstrate the gyroscopic phenomena of the momentum/velocity cross product as well as precession, nutation, and conservation of angular momentum, Closed loop experiments begin with basic rigid body control (see reverse page) to demonstrate fundamental principles. Reaction wheel experiments show the ramifications of providing control effort through a free-spinning base where practical issues of motor torque/speed and saturation become essential design factors for any such system. Gyroscopic torque control is studied and seen to provide extremely high control authority through actuating the cross-axis gimbal. This achieves dramatic high bandwidth and precision control.

MIMO experiments of the combined reaction and gyroscopic control modes evaluate relative performance of various design approaches and provide graphic demonstrations of large motion, complex system control. The system is then configured in off-nominal gimbal orientations where cross-coupling between the control modes is strong and effective multivariable control design is implemented.

The full nonlinear system model and many useful special cases are provided to support advanced research in areas of such as gain scheduling, workspace/trajectory planning, and singularity avoidance.



Nutation & Reaction Control *With all gimbals free and the rotor spinning, motor #2 is given an impulse command to excite the open loop nutation mode (upper left). Simple rate feedback measured at gimbals 2 & 4 with control torque at gimbal 2 is effective at damping the mode (bottom left). With the apparatus in a pure reaction wheel configuration, effective control of gimbal 3 position is easily implemented. Rotor speed in this mode is not controlled and is seen to be the integral of the control effort (right)*



Multi-variable Control *The apparatus is configured with all gimbals free and the rotor initialized to a nominal speed. The combined gyroscopic and reaction control may be accomplished through simple linear controllers designed for each output independently. This typically yields relatively low performance as seen at the gimbal 3 and 4 outputs in following sawtooth trajectories (left). Full multi-variable methodology such as the LQR design plotted at right can yield rapid & precise motion control .*

Turn-key Systems* for Easy Setup & Operation

The CMG system comes complete with all the hardware & software you need to efficiently perform a broad range of control experiments. Setup requires only three simple steps: 1) Install DSP b oard in standard PC slot, 2) Load software, 3) Plug in cables and begin. You can easily operate the system in minutes and perform meaningful experiments the very first hour!

*** "Plant Only" option available without DSP board & I/F software**

Quality Components Provide High System Performance

Range of Motion	Unlimited in 4 axes
Motors / actuators	High torque density rare earth type. 0.5 (spin) & 2.0 N-m stall torque
Actuator Design	TIming belt and 4.8:1 precision planetary gearhead (axis #2)
Sensors	High resolution optical encoders, 16,000 - 60,000 counts / axis rev.
Brakes	Fail-safe, 30 in-oz holding, zero backlash
Slip Rings	Sealed precious metal type, friction ≤ 2 in-oz, noise < 60mΩ
Inertial Switches ("g-switches)	Fail-safe type, 2.1 g actuation, precious metal contact
Hardare Safety	G-switch sensed high rates shut down power & apply brakes
Size & Weight	50x50x48 cm. (20x20x19in.), 16 kg. (35 lb.)

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