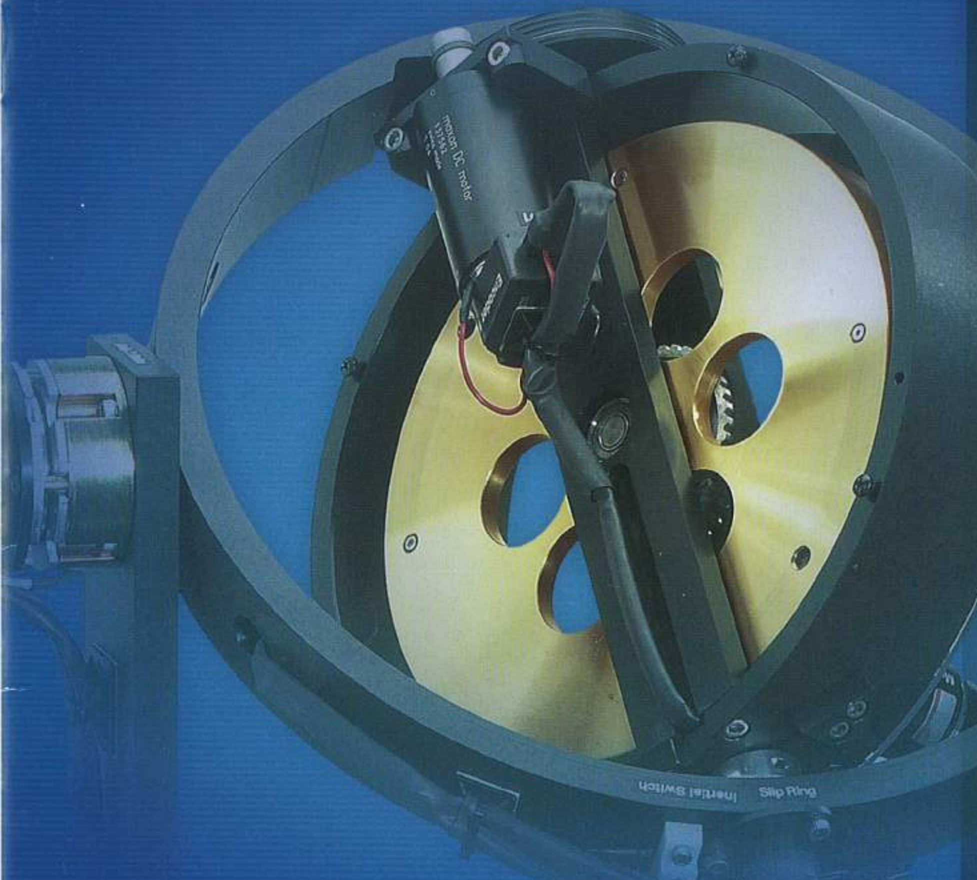
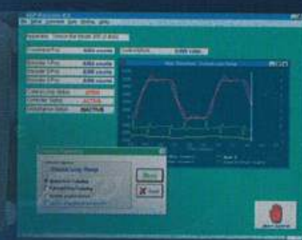
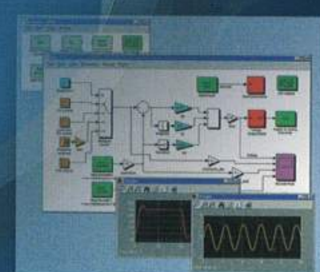
ecp
Educational Control Products

The most effective way to teach controls, dynamics, and vibrations







ADVANCED WORKSTATIONS FOR THE LABORATORY AND CLASSROOM

- Turn-Key Integration
- Precision Dynamics
- Multi-Platform Compatibility
- Legendary Reliability

1 Buckskin Court, Bell Canyon, CA 91307 • 800-486-0848 • www.ecpsystems.com

Advanced, Turn-key Systems

Our turn-key systems let you get straight to work using a wealth of advanced system features. Whether you're teaching basic concepts or conducting post doctorate research, ECP's complete packages minimize the hassle and maximize the empirical experience. Our versatile mechanisms, intuitive system software, step-by-step instructions, and detailed solutions, are proven to save you time.

All systems include a comprehensive set of experiments that bridge the learning gap between theory and real-world applications. Your students will benefit from the visually stimulating demonstrations each system provides. From the distinct oscillation modes of our torsional plant to the large nonlinear motion of our magnetic levitator, each system is designed to clearly show the open loop dynamics, then vividly demonstrate the effectiveness of closed loop control.

Rugged, Multi-use Mechanisms

Powerful, Intuitive, Interface Software

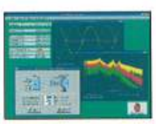
Industrial Grade I/O Electronics

High Speed Control Hardware

Interface Options For All Laboratory Environments

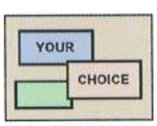
ECP Executive™ program provides a full set of linear controller forms, input trajectories, plotting and data management functions - all in a turn-key system

ECP Executive USR™ program provides the same easy-to-use features as the Executive while supporting fully general user-written control forms



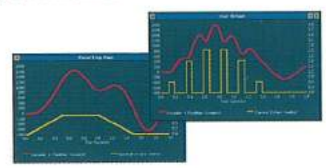
ECP Executive DYN™ turns our Model 205 and 210 systems into integrated dynamics and vibrations workstations - no control system experience required

ECP Extension to Real-time Windows Target lets you operate ECP turn-key systems in a real-time Simulink® environment via standard Mathworks products



"Plant-only" options provide the mechanism, electronics and control interfaces to operate ECP's quality apparatuses via third party hardware and software

Comprehensive Experiments



Contents

Systems That Perform To Perfection (And Don't Break!)

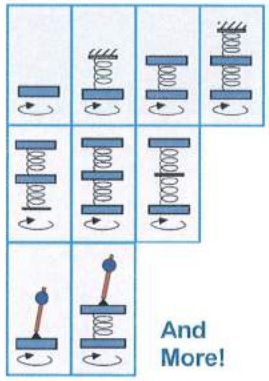
ECP's mechanisms are legendary for their quality, durability and multi-use utility. From the precision of our high resolution encoders and laser sensors to our high torque rare earth servo motors and ultra low friction duplexed bearing supports, we have cut no corners in providing the highest possible mechanism quality. This precision provides the truest possible plant dynamics. Systems of lesser quality can limit the types of control approaches that may be successfully employed. With ECP systems, if uncertainty in the plant dynamics is desired for study purposes, it may be easily introduced in a controlled manner and control effectiveness studied quantitatively.

The exceptional reliability of our systems pays high dividends in trouble-free operation. With hundreds of units in the field, we receive on average fewer than 1 per year returned for repair and have no reports of nonoperational equipment despite many being in continuous use for over 12 years! To back up our commitment to quality, we are the only manufacturer to provide a **full 3 year warranty** with all complete systems delivered in the US or Canada (contact ECP for warranty details). These handsome systems make visually stimulating controls and dynamics demonstrations. Our customers praise them in showcasing their laboratories to prospective students and visiting colleagues and during accreditation reviews.

Mechanism Highlights

Model 205
Torsional Apparatus

The Torsional apparatus is a proven multi-configurable workhorse that excels in heavy-use teaching laboratories. Its precise dynamics provides graphic demonstrations of rotational system controls and vibrations



And More!

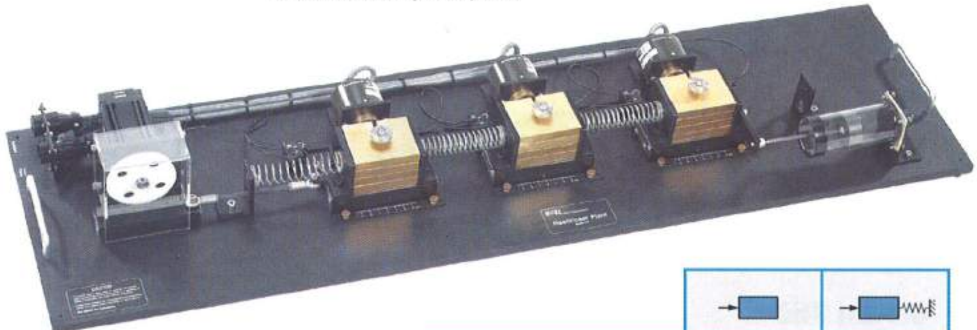
Adjustable
Inertias
Spring constants
System order
SISO, SIMO, MIMO³

Level	Config-urations	Options
Advanced – Introductory	6¹ 9² 18³	3 DOF, USR, DYN, S-LINK

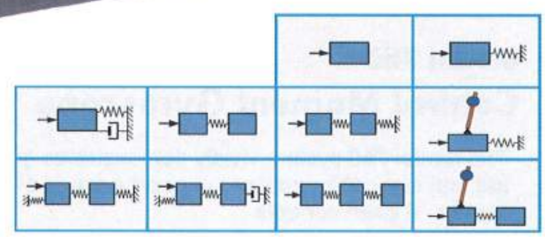
Level	Config-urations	Options
Advanced – Introductory	9¹ 16² 32³	3 DOF, USR, DYN, S-LINK

Model 210
Rectilinear Plant

This classical system is easily transformed into a variety of spring/mass/damper configurations commonly found in controls and dynamics text books. It provides a benchmark for control effectiveness and intuitive demonstration of vibration and controls principles.



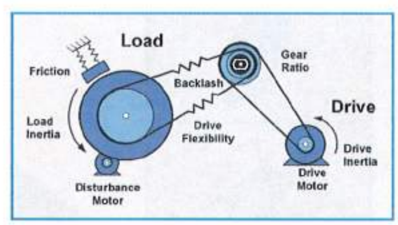
Adjustable
Inertias
Spring constants
Damping
System order
SISO, SIMO, MIMO³



And More!

Model 220
Industrial Plant Emulator

The Industrial Emulator provides a testbed for practical motion control implementation. Gear ratios and inertias are variable and non-ideal properties are applied and removed to demonstrate the effectiveness of mitigating control strategies.



Nonideal Properties - Typical In Industrial Applications - Are Easily Introduced And Removed

Level	Config-urations	Options
Advanced – Introductory	6	Std!, USR, S-LINK

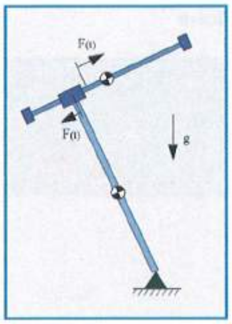
Adjustable
Inertias
Spring const.
System order
SISO, SIMO, MIMO³

Legend

- X¹ Number config's for basic system
- X² Config's with optional 3rd inertia
- X³ Config's with optional 2nd drive and USR software
- Second drive for disturbances & MIMO operation
- Inverted Pendulum accessory (A51)
- USR: USR Program (ECP Executive is std.)
- DYN: Executive DYN for dynamics & vibrations
- S-LINK: Real-time Simu-link via RTWT ECP Extension
- 3 DOF: Third Inertia & Feedback -adds 6th order config's

Mechanism Highlights

Model 505
ECP Inverted Pendulum



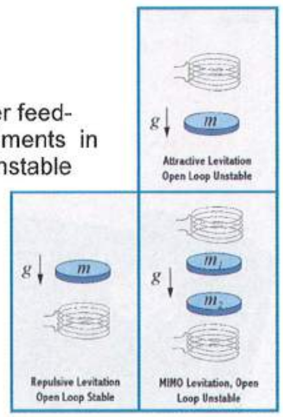
Level	Config-urations	Options
Advanced / Introductory	2	USR, S-LINK

ECP's inverted pendulum is a dynamically unique apparatus that is both nonminimum phase and conditionally stable (unlike a conventional inverted pendulum). Variable dynamic parameters provide a range of simple to highly challenging experiments in this self-contained system

Model 730
Magnetic Levitator

The MagLev system employs high flux magnetics and laser feedback to provide stimulating high amplitude levitation experiments in SISO, SIMO, and MIMO control of open loop stable and unstable systems.

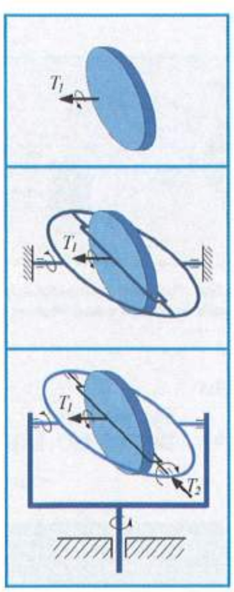
Level	Config-urations	Options
Advanced / Introductory	4	S-LINK, USR Std!



And More!

Model 750
Control Moment Gyroscope

The Model 750 system vividly demonstrates gyroscopic dynamics and control and is reconfigurable to support a range of simple and advanced experiments. It even controls our A51 pendulum throug˙ gyroscopic actuation!



And More!

Level	Config-urations	Options
Advanced / Introductory	5	S-LINK, USR Std!

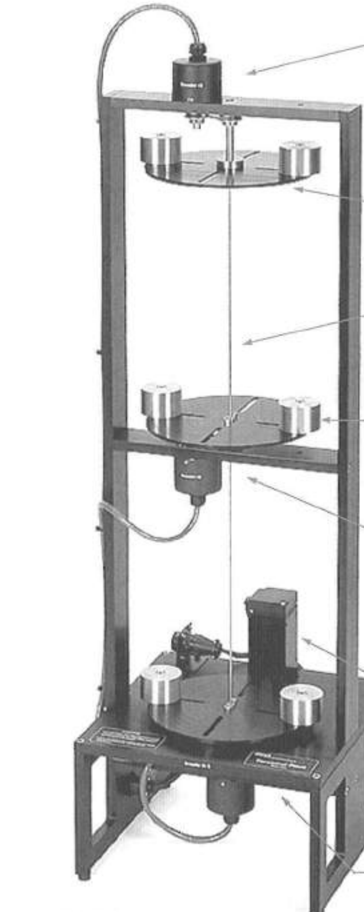
Accessory 51
Classical Pendulum

Step Response on Model 205 Torsional System

- Cost effective way to add experiments
- Inverted and non inverted operation
- Four independent adjustable parameters
- Self-inverting

ECP now offers two pendulum choices. The Pendulum Accessory (A51) is based on the classical inverted pendulum model and adds on to other stand-alone ECP systems using their actuators, base feedback, and electronics. Our ECP Inverted pendulum (Model 505, above) is a stand-alone system with unique dynamic characteristics. This system has proven itself in over 12 years of reliable in-field use and offers one of the lowest cost solutions for a stand-alone experiment commercially available.

Model 205
Torsional Apparatus



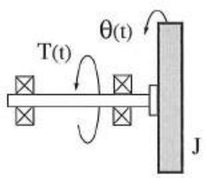
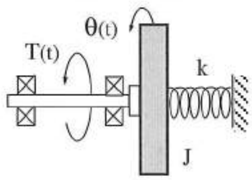
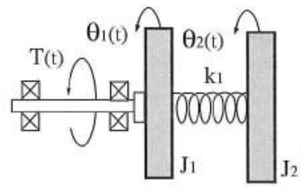
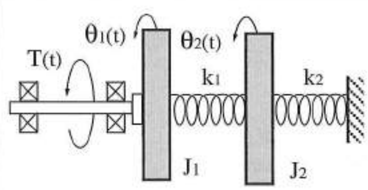
Three disk Model 205a shown. Basic Model 205 has 2 inertia disks

The Model 205 apparatus is a highly versatile platform that is ideal for introductory undergraduate lab use and intermediate controls study. It has also been used extensively in advanced research. In its several configurations, this system represents a broad and important class of practical plants including: rigid bodies, flexibility in drives, and coupled discrete vibrating systems. It easily transforms into second, fourth, and sixth (optional) order plants with collocated or noncollocated sensor / actuator control. An optional secondary drive may be positioned at any output (disk) to create a MIMO plant (requires *Executive USR™* software) and provides for the study of disturbance rejection.

The ability to readily adjust physical parameters such as inertia values and spring constants make it ideal for multiple student work group assignments. This apparatus closely follows its dynamic model and the theoretical predictions of open and closed loop behavior provided in the manual. It has proven to be highly robust and reliable in the field.

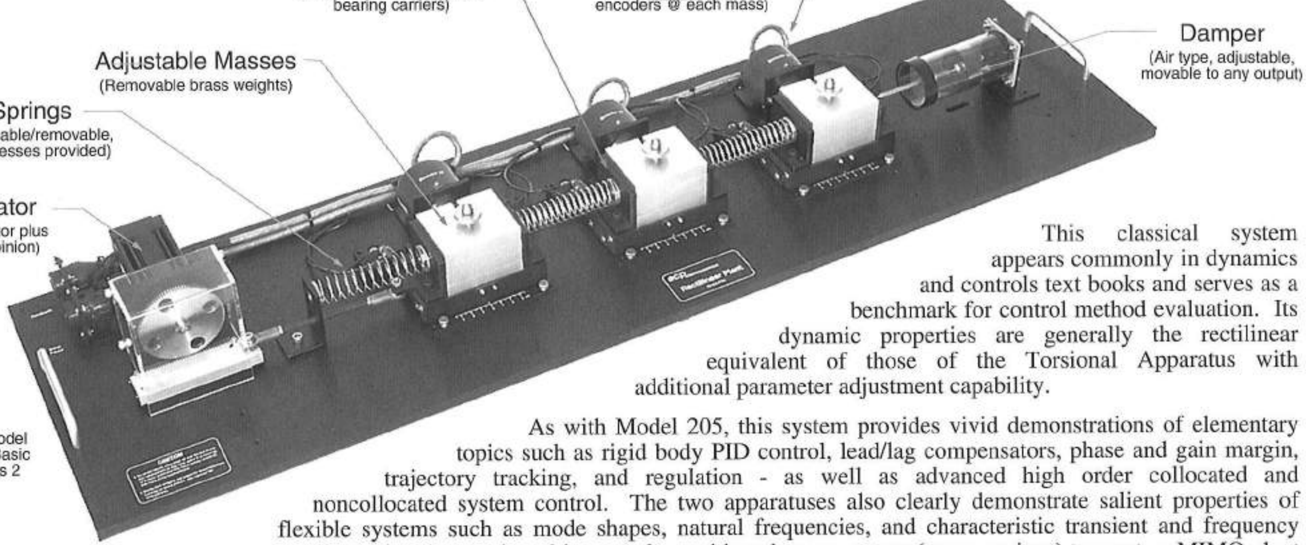
Configurations: 6 std, 9 with optional 3rd disk, 18 with secondary drive accessory
Dynamics: Adjustable to 2nd, 4th, and 6th (3 disk option) order, Systems types 0 and 2
I/O: SISO, SIMO, MIMO (with sec. drive accessory)
Poles and Zeros: Adjustable 0.8-7 Hz
Inertia Adjustment Ratio: 10:1
Spring Adjustment Ratio: 2:1 (certain configurations)
Feedback: High resolution encoder (16,000 count/rev)
Actuator: High torque brushless motor, 2.0 N-m
Bench-top size: 30x30x96 cm. (12x12x36 in.)
Safety Features: Amplifier over-current protection. In firmware (complete system only): relative displacement (spring) protection, over-speed protection, i^2t thermal protection

Easily Transforms to 6 Distinct Plants That Include...
(Nine plants with optional third disk*)

Plant Models	 ***Rigid body***	 ***Free-clamped***	 ***Free-free, 2 DOF***	 ***Free-clamped, 2 DOF***
Time Domain Equations	$J\ddot{\theta}(t) = T(t)$	$J\ddot{\theta}(t) + k\theta(t) = T(t)$	$J_1\ddot{\theta}_1(t) + k(\theta_1(t) - \theta_2(t)) = T(t)$ $J_2\ddot{\theta}_2(t) + k(\theta_2(t) - \theta_1(t)) = 0$	$J_1\ddot{\theta}_1(t) + k_1(\theta_1(t) - \theta_2(t)) + k_2\theta_1(t) = T(t)$ $J_2\ddot{\theta}_2(t) + k_1(\theta_2(t) - \theta_1(t)) + k_2\theta_2(t) = 0$
S-Domain Equations	$\frac{\theta(s)}{T(s)} = \frac{1}{J s^2}$	$\frac{\theta(s)}{T(s)} = \frac{1}{J s^2 + k}$	$\frac{\theta_1(s)}{T(s)} = \frac{J_2 s^2 + k}{D(s)},\ \frac{\theta_2(s)}{T(s)} = \frac{k}{D(s)}$ $D(s) = s^2\left(J_1 J_2 s^2 + (J_1 + J_2)k\right)$	$\frac{\theta_1(s)}{T(s)} = \frac{J_2 s^2 + k_1 + k_2}{D(s)},\ \frac{\theta_2(s)}{T(s)} = \frac{k_1}{D(s)}$ $D(s) = J_1 J_2 s^4 + \left(J_1(k_1 + k_2) + J_2 k_1\right)s^2 + k_1 k_2$
Characteristics	• Rigid body model. • Type 2 system. • See page 5.	• Classic spring-mass oscillator • Type 0 system • Single vibration mode	• Rigid body plus 1 oscillatory mode. • Type 2 system. • θ_1/T: 2 imag zeros, pole excess = 2 • θ_2/T: no zeros, pole excess = 4	• 2 oscillatory modes. • Type 0 system. • θ_1/T: 2 imag zeros, pole excess = 2 • θ_2/T: no zeros, pole excess = 4

* Three disk Model 205a plant provides sixth dynamic order with third normal mode.

Model 210
Rectilinear Plant



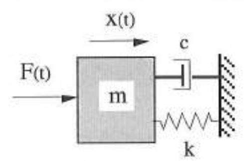
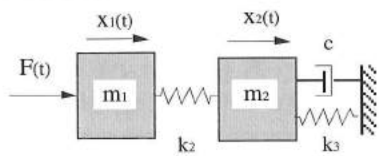
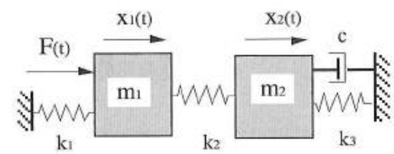
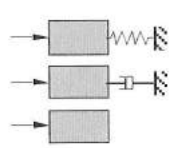
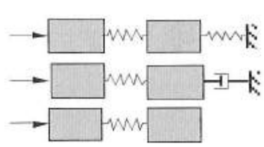
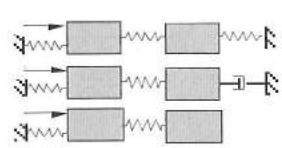
Three mass Model 210a shown. Basic Model 210 has 2 masses

This classical system appears commonly in dynamics and controls text books and serves as a benchmark for control method evaluation. Its dynamic properties are generally the rectilinear equivalent of those of the Torsional Apparatus with additional parameter adjustment capability.

As with Model 205, this system provides vivid demonstrations of elementary topics such as rigid body PID control, lead/lag compensators, phase and gain margin, trajectory tracking, and regulation - as well as advanced high order collocated and noncollocated system control. The two apparatuses also clearly demonstrate salient properties of flexible systems such as mode shapes, natural frequencies, and characteristic transient and frequency responses. An optional secondary drive may be positioned at any output (mass carriage) to create a MIMO plant (requires Executive USR™ software) and provide for the study of disturbance rejection.

Configurations: 12 std, 16 with opt. 3rd mass, 18 with second drive accessory	Damping Adjustment Ratio: >10:1
Dynamics: 2nd, 4th, and 6th (3 mass option) order, Systems types 0, 1, and 2	Feedback: High resolution encoder (160 count/mm)
I/O: SISO, SIMO, MIMO (with sec. drive accessory)	High torque brushless servo motor, precision rack & pinion , 8 N output
Poles and Zeros: Adjustable 1.5-7 Hz	Bench-top size: 31x66x15 cm. (12x26x6 in.)
Mass Adjustment Ratio: 5:1	Safety Features: Amplifier over-current protection, motion limit micro-switches & cushions. In firmware (complete system only): relative displacement protection, over-speed protection, i2t thermal protection
Spring Adjustment Ratio: 2:1 (certain configurations)	

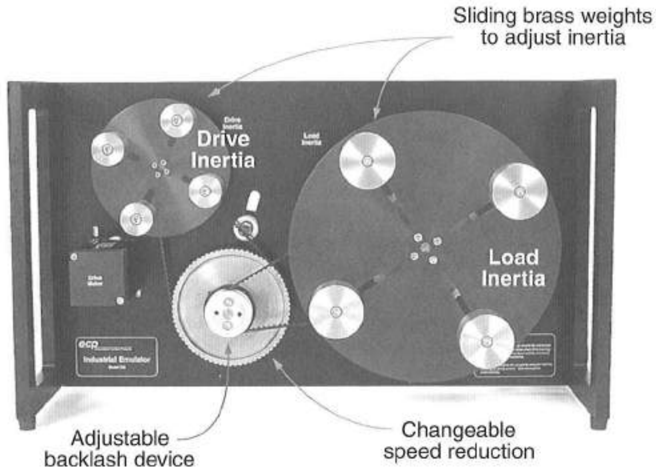
Transforms to Twelve Distinct Plants
(Sixteen plants with optional third mass)

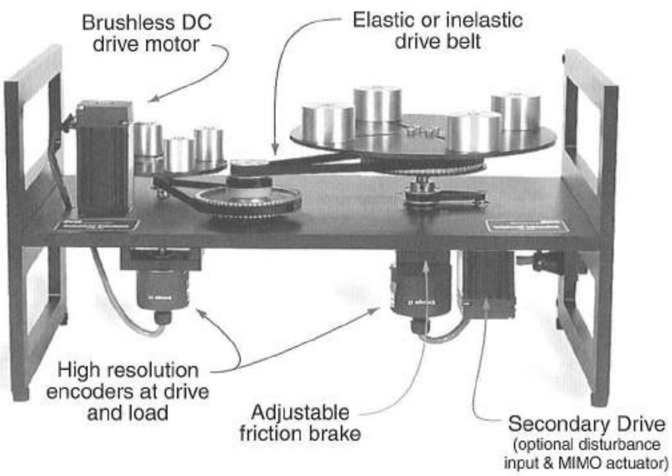
Plant Models	 ***Spring / mass / damper***	 ***Free - constrained, 2 DOF***	 ***Constrained - constrained, 2 DOF***
Additional Configurations			
Time Domain Equations*	$m\ddot{x}(t) + c\dot{x} + kx(t) = F(t)$	$m_1\ddot{x}_1(t)+k_2x_1(t)-k_2x_2(t) = F(t)$ $m_2\ddot{x}_2(t)+c\dot{x}_2(t)-k_2x_1(t)+(k_2+k_3)x_2(t) = 0$	$m_1\ddot{x}_1(t)+(k_1+k_2)x_1(t)-k_2x_2(t) = F(t)$ $m_2\ddot{x}_2(t)+c\dot{x}_2(t)-k_2x_1(t)+(k_2+k_3)x_2(t) = 0$
S-Domain Equations*	$\frac{x(s)}{F(s)}=\frac{1}{ms^2+cs+k}$	$\frac{x_1(s)}{F(s)}=\frac{m_2s^2+cs+k_2+k_3}{D(s)}, \quad \frac{x_2(s)}{F(s)}=\frac{k_2}{D(s)}$ $D(s)=(m_1s^2+k_2)(m_2s^2+cs+k_2+k_3)-k_2^2$	$\frac{x_1(s)}{F(s)}=\frac{m_2s^2+cs+k_2+k_3}{D(s)}, \quad \frac{x_2(s)}{F(s)}=\frac{k_2}{D(s)}$ $D(s)=(m_1s^2+k_1+k_2)(m_2s^2+cs+k_2+k_3)-k_2^2$
Characteristics	• Classic damped oscillator. • Pole excess = 2. • Configurable to type 0,1, or 2 system.	• Two damped modes. • x_1/F: "Damped" zero, pole excess = 2. • x_2/F: "no zeros, pole excess = 4. • Configurable to type 0,1, or 2 system.	• Two damped modes. • x_1/F: "Damped" zero, pole excess = 2. • x_2/F: "no zeros, pole excess = 4. • All configurations type 0.

*Three mass Model 210a has dynamic order up to six with three oscillatory modes.

Model 220

Industrial Plant Emulator



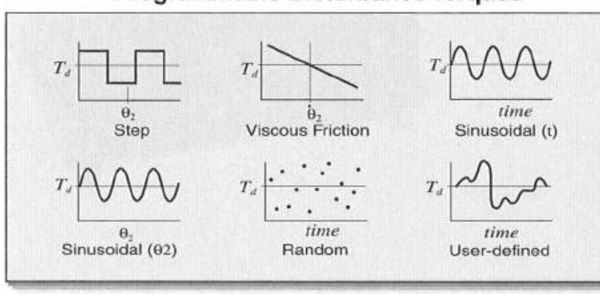


Testbed for Practical Control Training

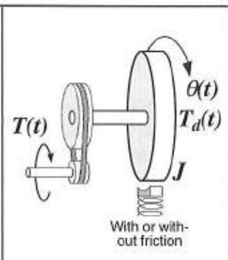
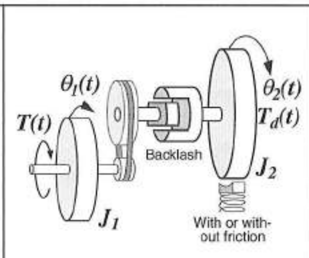
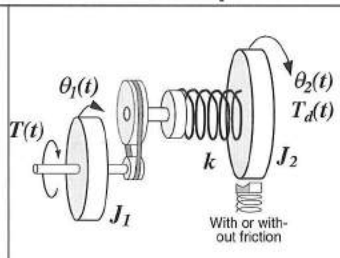
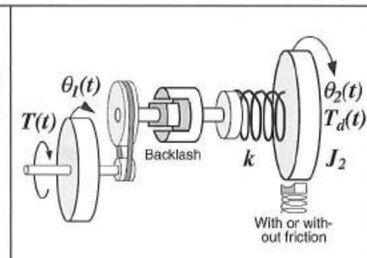
This system is ideal for teaching practical control of modern industrial equipment such as spindle drives, turntables, conveyors, machine tools, and automated assembly machines. Such plants are readily emulated using the many available configurations of the apparatus. Its adjustable dynamic parameters, and ability to introduce or remove non-ideal properties in a controlled manner make it a perfect selection for industrial servo control training. An optional secondary drive provides for programmable disturbance inputs and with the optional Executive USR™ software, the apparatus becomes a full MIMO testbed.

Actuator Inertia, J_1:	Adjustable, .0004 to .00245 kg-m²
Load Inertia, J_2:	Adjustable, .005 to .025 kg-m²
Gear ratio (GR):	6 speeds from 1.5:1 to 24:1
Backlash:	Adjustable, 0 to 90 motor degrees
Drive flexibility:	Adjustable, Rigid to 1.0 Hz flex freq.
Coulomb friction brake:	Adjustable, 0 to > 10 N-m
I/O: SISO, SIMO, MIMO	
Feedback: High resolution encoder, 16,000 counts/rev.	
Actuator: High torque brushless DC servo motor, 2.0 N-m	
Secondary Drive (optional): High torque brushless , 2.0 N-m	
Bench-top size: 30x51x12 cm. (12x20x12 in.)	
Safety Features: Plexiglass® cover, amplifier over-current protection. In firmware (complete system only): relative displacement protection, over-speed protection, i²t thermal protection	

Programmable Disturbance Torques

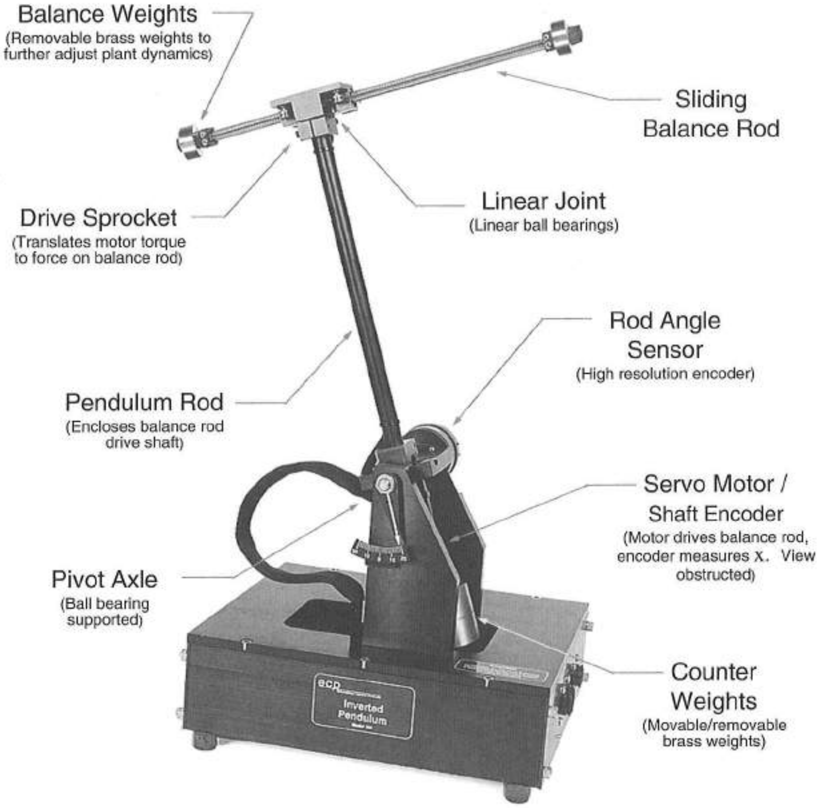


Introduce or Remove Non-ideal Properties

	Basic Rigid Body	Drive / Load with Backlash	Drive / Load with Flexibility	Drive / Load with Backlash & Flexibility
Plant Model				
"Exact" Time Domain (expressions do not include all introducible parameters)	$J\ddot{\theta} + c\dot{\theta} = n_g T$ where n_g is the gear ratio	$J_2\ddot{\theta}_2 + c_2\dot{\theta}_2 + f_2 sign(\dot{\theta}_2)$ $= F_{bklsh}(\theta_2 - \theta_1) * n_g(T - J_1\ddot{\theta}_1)$ where: $F_{bklsh}(\bullet) = 0$ when $0 < \bullet <$ backlash $= 1$ otherwise; f_2 is the Coulomb friction coef. Friction only at θ_2 assumed	$J_1\ddot{\theta}_1 + c_1\dot{\theta}_1 + k(n_g^{-2}\theta_1 - n_g^{-1}\theta_2) = T$ $J_2\ddot{\theta}_2 + c_2\dot{\theta}_2 + k(\theta_2 - n_g^{-1}\theta_1) = 0$	$J_1\ddot{\theta}_1 + c_1\dot{\theta}_1 + f_1 sign(\dot{\theta}_1)$ $+ F_{bklsh}(\theta_2 - \theta_1) * k(n_g^{-2}\theta_1 - n_g^{-1}\theta_2) = T$ $J_2 n_g^2\ddot{\theta}_2 + c_2\dot{\theta}_2 + f_2 sign(\dot{\theta}_2)$ $+ F_{bklsh}(\theta_2 - \theta_1) * k(\theta_2 - n_g^{-1}\theta_1) = 0$
S-Domain (Nonlinear terms linearized)	$\frac{\theta_1(s)}{T_D(s)} = \frac{1}{s((J_2 + n_g^2 J_1)s + c_2)}$ $\theta_1 = n_g\theta_2$		$\frac{\theta_1(s)}{T(s)} = \frac{J_2 s^2 + c_2 s + k}{D(s)}$ $\frac{\theta_2(s)}{T(s)} = \frac{k/n_g}{D(s)}$ $D(s) = J_1J_2s^4 + (J_1c_2 + J_2c_1)s^3 + (J_1k + J_2n_g^{-2}k + c_1c_2)s^2 + (c_1k + c_2n_g^{-2}k)s$	

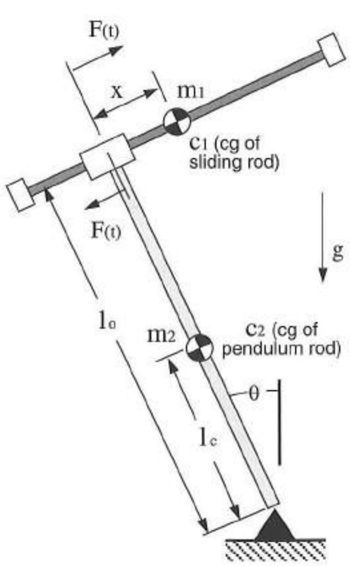
Plant Features

Model 505
ECP Inverted Pendulum



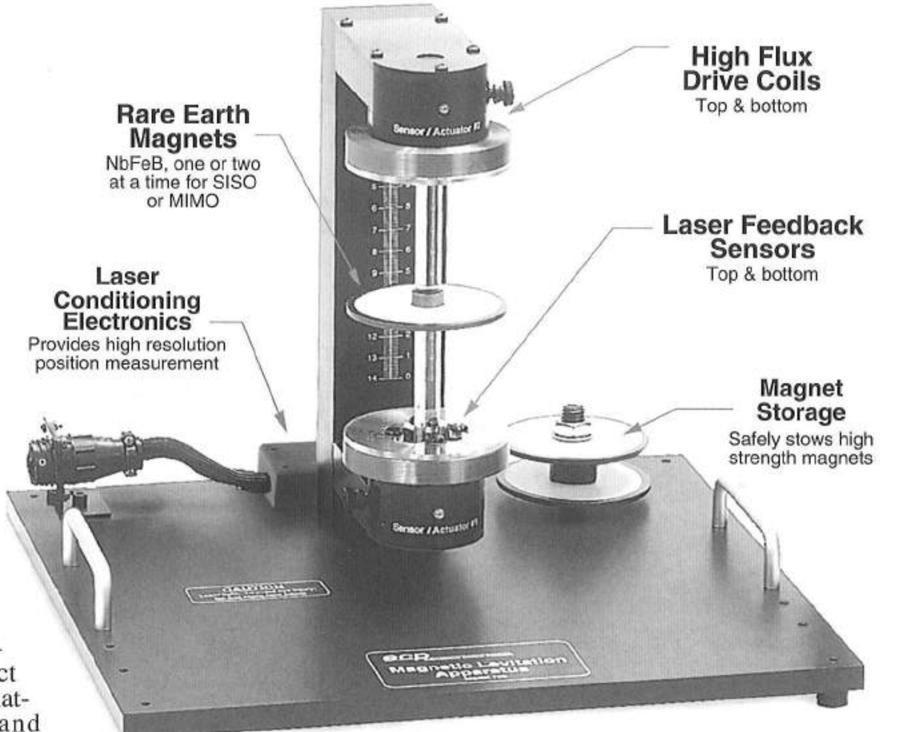
This unique ECP design vividly demonstrates the need for and effectiveness of closed loop control. It is *not* the conventional rod-on-cart inverted pendulum, but rather, it steers a horizontal balancing rod in the presence of gravity to control the vertical pendulum rod. As detailed in the manual, the plant has both right half plane poles and zeros as well as kinematic and gravitationally coupled nonlinearities. By adjusting mass properties, these roots may be varied to make the control problem range from being relatively simple to theoretically impossible! The system includes removable and adjustable moment arm counter-weights on the vertical and horizontal rods for quick adjustment of the plant dynamics. It features linear and rotary ball bearings at the joints for low friction and consistent dynamic properties.

Dynamics: 4th order, nonminimum phase, open loop unstable, kinematic & gravitationally coupled nonlinearities
Parameter Adjustment: Adjustable vertical and horizontal rod mass, inertia, and CG offset.
I/O: SISO, SIMO,
Poles: Adjustable 0.4-1.2 Hz
Feedback: High res. encoders (16,000 count/rev, θ, 44,000 count/m, x)
Actuator: High Torque density, rare earth magnet type
Bench-top size: 30x30x40 cm. (12x12x16 in.)
Safety Features: Travel limit microswitches (horizontal rod) , fail-safe shutdown, limit cushions (vertical rod), amplifier over-current protection. In firmware (complete system only): i2t thermal protection

Plant Model		*Dynamic Equations*	*Characteristics*
	*"Exact"*	$m_1\ddot{x}(t)+m_1 l_o\ddot{\theta}(t) - m_1 x(t)\dot{\theta}(t)^2 - m_1 g\sin\theta(t) = F(t)$ $m_1 l_o\ddot{x}(t)+J_o(x)\ddot{\theta}(t)+2m_1 x(t)\dot{x}(t)\dot{\theta}(t) - (m_1 l_o+ m_2 l_c)g\sin\theta(t) - m_1 g x(t)\cos\theta(t) = 0$ $J_o(x) = J_1+m_1(l_o^2+ x^2) +J_1+m_2 l_c^2$	• Nonlinearities in kinematic constraints and coordinate dependent mass properties.
	Linearized Time Domain	$m_1\ddot{x}(t)+m_1 l_o\ddot{\theta}(t) - mg\,\theta(t) = F(t)$ $m_1 l_o\ddot{x}(t)+J_o^*\ddot{\theta}(t) - (m_1 l_c+ m_2 l_o)g\theta(t) - m_2 g x(t) = 0$ $J_o^* = J_o\big\|_{x=0}$	• Linearization about x = 0, θ = 0 shown to be valid for many control schemes.
	S-Domain	$\frac{\theta(s)}{F(t)} = \frac{-(l_o s^2 - g)}{(J_o^* - m_1 l_o^2)s^4 + (m_2 l_o - m_1 l_c)g\,s^2 - m_2 g^2}$	• One RHP, 2 oscillatory poles. • Nonmin phase (RHP zero). • Attainable bandwidth bounded from above and below by RHP roots.

Model 730

MagLev Apparatus

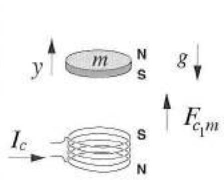
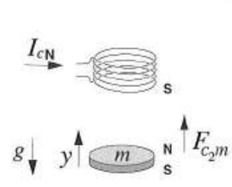
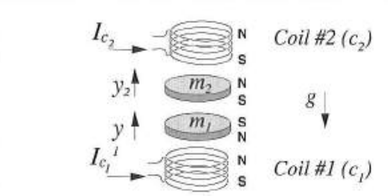
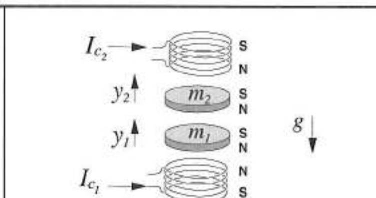


Configurations: 6 (those shown below plus 2 SIMO)
Dynamics: Highly nonlinear magnetic field, open loop stable and unstable
I/O: SISO, SIMO, MIMO
Feedback: High resolution lasers (10 micron resolution, 6 cm. range)
Actuator: High flux magnetic coil, rare earth (NbFeB) magnets
Bench-top size: 38x38x30 cm. (15x15x12 in.)
Safety Features: Over-current protection, passive laser eye protection, magnet travel limit cushions, i^2t thermal protection (complete system only)

ECP's unique MagLev apparatus dramatically demonstrates closed loop levitation of ferro-magnetic elements. The apparatus includes laser feedback and high flux magnetics to effect large displacements and provide visually stimulating eperiments in closed loop tracking and regulation. The system is quickly set up in the open loop stable and unstable (repulsive and attractive fields) configurations shown. By adding a second magnet, two SIMO plants may be created, and by driving both actuators with both magnets, MIMO control is studied. The inherent magnetic field nonlinearities may be inverted via provided real-time algorithms for linear control study or the full system dynamics may be examined. Disturbances may be introduced via the second drive coil for demonstrating system regulation in SISO operation.

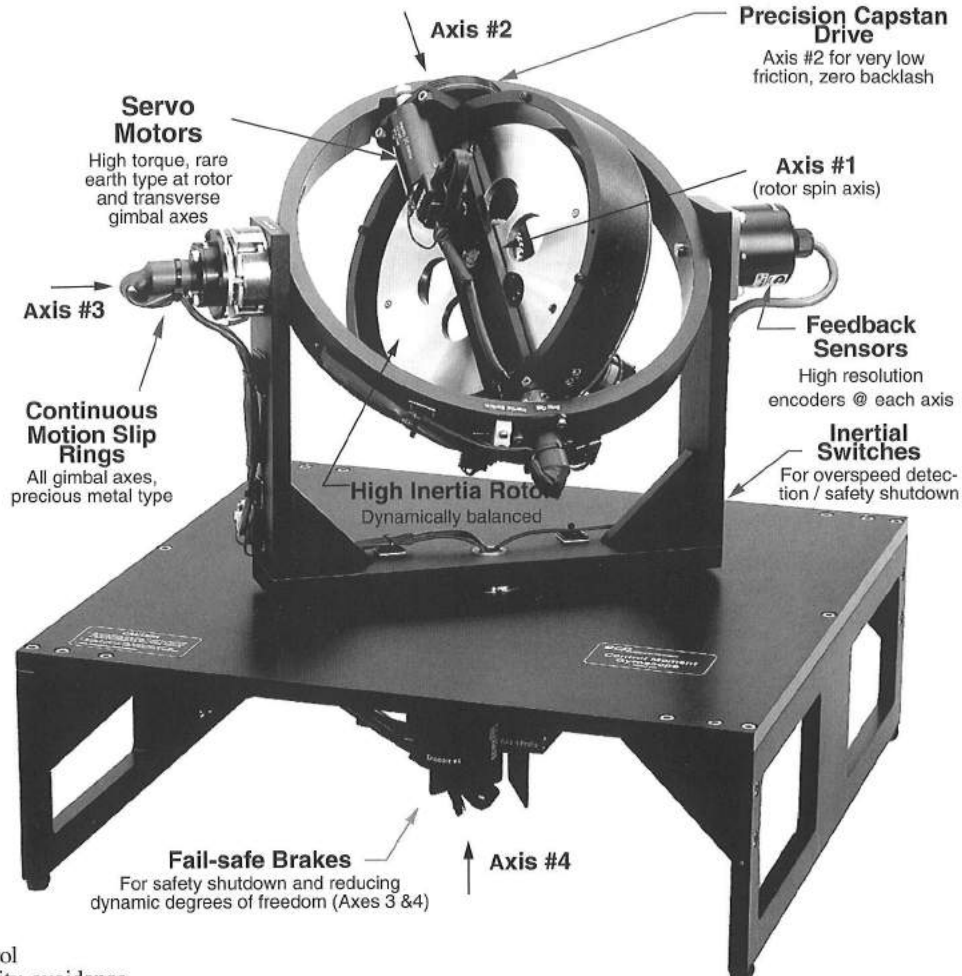
This versatile plant offers far more multi-use flexibility and greater levitation travel range than other educational maglev systems system and hence provides greater educational utility and visual impact in demonstrations.

Provides A Variety Of SISO & MIMO, Stable & Unstable Plant Configurations

Configuration	 **Repulsive Levitation Open Loop Stable**	 **Attractive Levitation Open Loop Unstable**	 **MIMO Levitation, Locally Open Loop Stable**	 **MIMO Levitation, Open Loop Unstable**
Equations of Motion	$m\ddot{y}+c\dot{y} = F_{c_1m} - mg$ *("c" is very small friction modeled as viscous)*	$m\ddot{y}+c\dot{y} = F_{c_2m} - mg$	$m_1\ddot{y}_1+c\dot{y}_1 = F_{c_1m_1}+F_{m_1m_2}+F_{c_2m_1}+m_1g$ $m_2\ddot{y}_2+c\dot{y}_2 = F_{c_1m_2}+F_{m_1m_2}+F_{c_2m_2}+m_2g$	$m_1\ddot{y}_1+c\dot{y}_1 = F_{c_1m_1}-F_{m_1m_2}+F_{c_2m_1}+m_1g$ $m_2\ddot{y}_2+c\dot{y}_2 = F_{c_1m_2}-F_{m_1m_2}+F_{c_2m_2}+m_2g$
Linearized Forms (about some coil current / gravity equilibrium)	$m\ddot{y}'+c\dot{y}'+ky' = k_F I_c'$	$m\ddot{y}'+c\dot{y}'-ky' = k_F I_c'$	$m_1\ddot{y}_1'+c\dot{y}_1'+(k_1+k_2-k_3)y_1'-k_2y_2' = k_{F_{11}}I_{c_1}'+k_{F_{21}}I_{c_2}'$ $m_2\ddot{y}_2'+c\dot{y}_2'+(k_2-k_4+k_5)y_2'-k_2y_1' = k_{F_{12}}I_{c_1}'+k_{F_{22}}I_{c_2}'$ *Stable* $\forall\ (k_1+k_2)\le k_3$ *and* $(k_2+k_5)\le k_4$	$m_1\ddot{y}_1'+c\dot{y}_1'+(k_1-k_2-k_3)y_1'+k_2y_2' = k_{F_{11}}I_{c_1}'+k_{F_{21}}I_{c_2}'$ $m_2\ddot{y}_2'+c\dot{y}_2'-(k_2+k_4-k_5)y_2'+k_2y_1' = k_{F_{12}}I_{c_1}'+k_{F_{22}}I_{c_2}'$ *Stable* $\forall\ k_1\ge(k_2+k_3)$ *and* $k_5\ge(k_2+k_4)$
Transfer Function (selected linearized plant)	$\dfrac{Y}{I_c'} = \dfrac{k_F}{ms^2+cs+k}$	*TF of above left stable system*	$\begin{bmatrix} m_1s^2+cs+(k_1+k_2-k_3) & -k_2 \\ -k_2 & m_2s^2+cs+(k_2+k_5-k_4) \end{bmatrix}\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} k_{F_{11}} & k_{F_{12}} \\ k_{F_{21}} & k_{F_{22}} \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$	*TF of above left system; stability assumed*
Notation	$F_{c_1m} = \dfrac{k_{cm}I_c}{(y+d)^{N_{cm}}}$, $F_{c_2m} = \dfrac{k_{cm}I_c}{(d-y)^{N_{cm}}}$ *" ' " denotes value relative to some equilibrium pt.* k_{cm}*,* d*, &* N_{cm} *are positive constants,* $(N_{cm}\approx 4)$		$F_{c_1m_1} = \dfrac{k_{cm}I_{c_1}}{(y_1+d_{c_1m_1})^{N_{cm}}}$ $F_{m_1m_2} = \dfrac{k_{mm}}{(y_1-y_2+d_{m_1m_2})^{N_{mm}}}$ $F_{c_1m_2} = \dfrac{-k_{cm}I_{c_1}}{(y_2-d_{c_1m_2})^{N_{cm}}}$ $F_{c_2m_2} = \dfrac{-k_{cm}I_{c_2}}{(y_2-d_{c_2m_2})^{N_{cm}}}$	$F_{c_2m_1} = \dfrac{k_{cm}I_2}{(y_1+d_{c_2m_1})^{N_{cm}}}$ *Notation similar to that for SISO* $(N_{mm}\approx 4)$

Plant Features

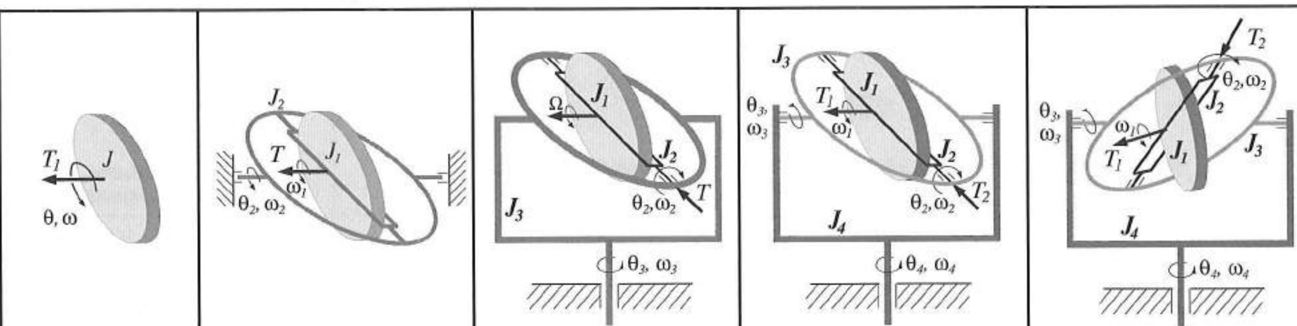
Model 750
Control Moment Gyroscope



Configurations: 5 about std. gimbal angles plus any user selected gimbal angles. Brakes lock desired gimbals for lower order config's.
Dynamics: linear in neighborhood of nom. gimbal angles becoming highly nonlinear with singularities @ large angles.
I/O: SISO, SIMO, MIMO
Feedback: high res. encoders (16,000 counts/rev, gimbals 3&4; 24,000 counts/rev, gimbal 2; 6700 counts/rev gimbal 1)
Actuator: High torque, rare earth magnet motors, Axis 2: capstan drive, 3 N-m output. Axis 1: timing belt drive 1 N-m output
Bench-top size: 51x51x53 cm. (20x20x121 in.)
Safety Features: Inertial switch rate detection, fail-safe brakes, fail-safe system power-down, rotor speed limit, amplifier over-current protection, micro-limit switches and limit cushions for axis #2. In firmware: gimbal rate limits, rotor speed limits, i^2t thermal protection (complete system only)

ECP's four axis Control Moment Gyroscope is a dynamically rich system that provides superb demonstrations of multi-DOF rigid body control. Elementary experiments are readily performed that graphically show the phenomenon of gyroscopic torque and its use in precision high authority control. 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. The apparatus includes low friction slip rings at gimbals 2, 3 and 4 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 / Gyroscopi c positioner (Special case)	Reaction / Gyroscopi c positioner (General Case)
Equations of Motion	$J\ddot{\theta} = T$ **Brakes are applied on all axes except rotor to minimize system order**	$J_2\dot{\omega} = -T$ $\omega_1 = \omega_{1_o} + \int_0^t T(\tau)/J_1\, d\tau$ **Brakes applied at second and fourth axes - see reverse page**	*For small θ_2 and symmetric mass properties:* $\dot{\omega}_3 = \big(\Omega\omega_2 J_1^2 + (T_1 + (J_1\theta_4)/J_{eq}$ $+2(J_2^2 - J_1^1 - J_2^3))\omega_2\omega_3)$ *where J_i^j is the jth diagonal element of $\mathbf{J_i}$ 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)*	$\dot{\omega} = \left[f(\theta_k, \omega_i, J_i^j)\right]\omega$ $+ \left[g(\theta_k, J_i^j)\right]\mathbf{T}$ *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**

No Competing Systems Approach ECP's Breadth & Depth Of Experiments

A full set of experiments is provided with each system that vividly demonstrates important control system principals. Where competing products include only one or two control experiments with each system, ECP provides a broad range of fully documented experiments and supplemental exercises. This enables you to select from the provided topics to tailor experimental activities to your specific curriculum needs. Our experiments typically cover topics ranging from basic low order plant identification and control design to high order regulation with nonlinear compensation in MIMO systems. Detailed instructions for the students and complete solutions for the instructor greatly reduce your time in class preparation and assignment grading. Additional features such as summary review sections, Matlab™ design and analysis scripts, and instructor optional assignments, let you efficiently utilize the system's broad functionality. Extensive use of graphical figures provides a concise depiction of control theory, experimental procedures, and expected results.

Experiments Common to Models 205 & 210

1. Plant Identification: Identifies the plant inertias, spring constants, damping, and hardware gains using classical techniques of measuring natural frequency and damping. These parameters are then used to construct numerical plant models for control design. (You are of course provided with numerical models, so that these tests are not necessary for system use).

2. Second Order System Fundamentals: This important introductory lesson uses rigid body PID control to show students the effect of proportional, derivative, and integral control gains on the experimental transient and frequency responses. It shows the physical meaning of Bode phase and gain plots, correlation of classical time and frequency domain characteristics, and the effect of control gains on S-plane roots and stability margin. The experiment is further described in Figure 2.

3. Disturbance Attenuation: This experiment utilizes the secondary drive accessory to impart low and high frequency disturbances on the system. As shown in Figure 3, students implement various controllers and learn that the effectiveness of the system in regulating against disturbances can be predicted by the open and closed loop system gain characteristics and the frequency spectrum of the of the disturbance itself.

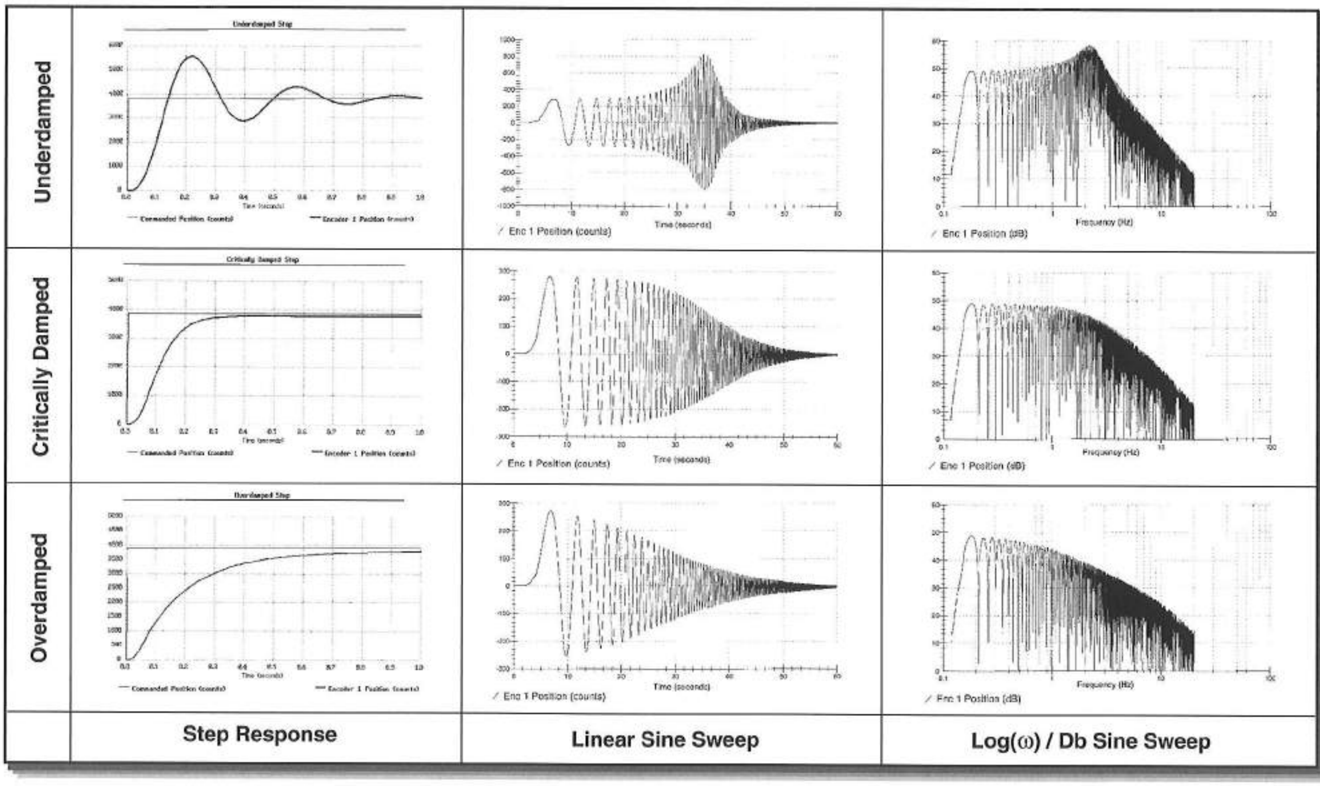


Figure 2. Fundamentals of Second Order Systems

This introductory experiment begins with students implementing, P, D, and I gains individually and physically manipulating the apparatus to actually "feel" their control actions. Students then design the controller to provide specified ω and various ζ and obtain the step and frequency responses shown. The linear sine sweep data best reflects the system motion as physically observed. The same data plotted with ECP's unique Log(ω) / Db scaling functions graphically relates these observations to the Bode plot format common in the literature. An integrator is added and observed to eliminate steady-state error and cause the characteristic overshoot and frequency response resonance. A comprehensive set of exercises examine the characteristic S-plane roots, the effect of various system parameters on ω and ζ, classic step response characteristics, phase and gain margins, sensitivity to parameter changes, and correlation of time and frequency domain characteristics.

Experiments

4. Collocated Control With 2 DOF Plant: This experiment implements *collocated* (sensor & actuator at same location) closed loop control on the "Free-Free, 2-DOF" plant. It shows that high performance can be achieved at the collocation, but unacceptable tracking results at the noncollocation (θ_2, or x_2) due to structural flexibility. Experimental frequency responses show a flat gain characteristic to the system bandwidth at the collocation but a sharp resonance appears in the noncollocated response. (see Figures 6 & 7a,b - Model 220 Experiments).

5. PID Plus Notch Filter Control: *Noncollocated* control is demonstrated using a notch filter to suppress the oscillatory plant dynamics. Then a simple PD control loop is closed about the noncollocated output with the student interactively varying gains and observing the system response. The design is analyzed using root locus techniques and improvement in attainable performance at the noncollocation over collocated control is clearly shown.

6. Full State Feedback LQR Control: This experiment designs and implements an LQR controller for noncollocated control of the SIMO plant. Experimental results show the effectiveness of the scheme in dealing with structural flexibility. In response to a step command (see Figure 4), the collocated position (x_1) moves wildly as the control minimizes the error at the noncollocation x_2. The sine sweep (frequency response - see Figure 4) of this system clearly shows the system resonance and zero at x_1 with a fairly flat response at the desired output, x_2. The greater high frequency gain slope at x_2 v. x_1 due to the greater pole excess is also clearly seen.

7. Successive Loop / Pole Placement Control: This experiment utilizes classical successive loop SIMO high authority/low authority design where a high gain inner loop effectively kills model uncertainty and a pole placement design of the outer loop yields closed loop behavior nearly identical to those of the desired relatively high bandwidth system. The success of the design is demonstrated in experimental tracking and frequency response measurements.

8. Robustness To Parameter Variations: The three flexible structure controllers (notch filter, LQR, successive loop) are compared for their performance and stability in the face of changing plant parameters. The mechanisms' easy parameter change features are used to vary the noncollocated inertia from the nominal value, J_{2o}, to $\frac{1}{2} J_{2o}$, then $2 J_{2o}$. This real-world scenario, change in inertia at the payload end of flexible linkages, is representative of many industrial and aerospace applications. The results show that all control approaches remain stable but differ greatly in their ability to perform well in the changing conditions.

9. Practical Control Issues: Important issues that affect all physical sampled data systems are demonstrated. These include the effects of sample period on closed loop stability and transient behavior, sensor quantization and control effort saturation, and finite wordlength. After demonstrating these effects on the physical system, the underlying theory is presented, and effective mitigating approaches are demonstrated.

10. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of virtually any topic in control systems. All experimental topics described on page 14 are applicable here.

Comprehensive Coverage

You receive the following tests and exercises with our Model 205 & 210 systems.

- Dynamic Modeling, Model Order Reduction
- System Identification
- Rigid Body PD / PID Control
- Fundamental Open & Closed Loop Properties
  - Transient Responses
  - Frequency Response
  - Rigid & Flexible Body Characteristics
  - Time v. Frequency domain correlation
- Phase & Gain Margin
- Root Locus Design
- Nyquist Stability
- Static Servo Stiffness
- Sensitivity to Parameter Changes
- Control Robustness
- Static Servo Stiffness
- Tracking Control
- Disturbance Rejection*
- Flexible Structure Control:
  - Notch Filters
  - Collocated Sensor / Actuator
  - Noncollocated Control
  - Low Authority / High Authority Loops
  - Pole Placement
  - Linear Quadratic Regulator
- Practical Control Issues:
  - Drive Saturation
  - Sensor quantization
  - Discrete time sampling
  - Custom Real-time control execution
- AND MORE!

*requires optional equipment

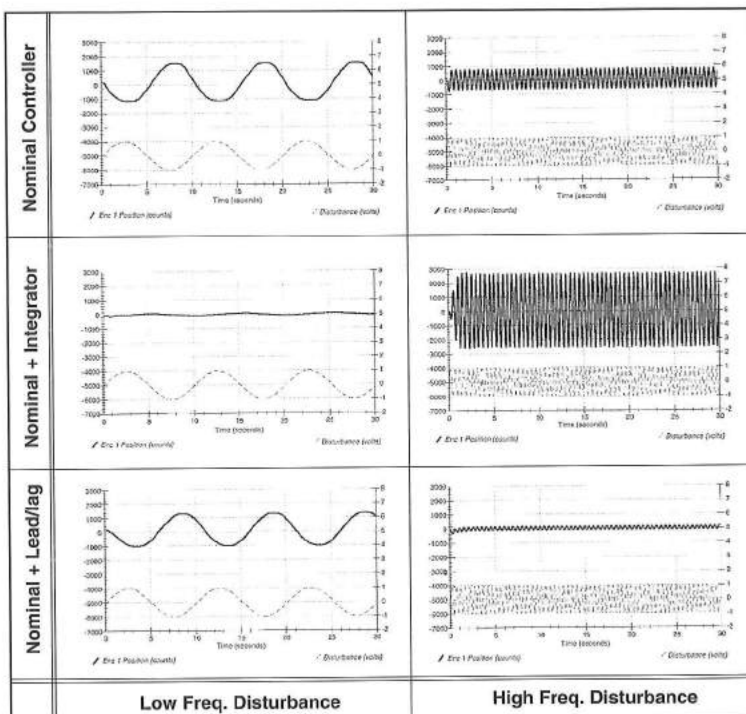


Figure 3. Disturbance Rejection / Control Effectiveness

This experiment shows students the essential role of feedback in attentuating disturbances. Students design a simple linear controller for a second order plant. Integral action and a lead/lag filter are then designed separately to augment the controller. Tests show that the nominal controller provides only moderate attenuation of both low and high frequency disturbances. With the added integrator, the low frequency disturbance is greatly attenuated, but the high frequency one is actually amplified. The lead/lag filter has little effect at low frequency but is effective at high frequency. These characteristics are studied in terms of the open and closed loop Bode plots and the student learns that the effectiveness of control regulation depends the controller gain characteristic and the frequency band of the disturbance itself.

Model 220 Industrial Plant Emulator Experiments

1. Plant Identification. Identifies the plant inertias, spring constants, damping, gear ratios, and hardware gains. (similar to test series #1 in the Model 205 $ 210 Experiments)

2. Fundamentals Of Second Order Systems. This series of experiments and exercise is essentially identical to test series #2 in the Model 205 $ 210 Experiments (see also Figure 2).

3. Disturbance Attenuation. These tests are similar to series #3 in the Model 205 & 210 Experiments (see Figure 3) with the additional study of the effect of gear ratio in low and high frequency disturbance attenuation. (utilizes built-in secon-dary drive, does not require additional drive accessory)

4. Collocated Control With 2 DOF Plant. This experiment implements *collocated* (sensor & actuator at same location) closed loop control on the "Free-Free, 2-DOF" plant and shows that acceptable performance is achievable under high gain control at the collocation (drive), but an oscillatory response results at the noncollocation (load). The oscillations may be reduced under lower gain but reduced collocated performance and increased steady-state error result. See Figures 6 and 7a,b.

5. PID Plus Notch Filter Control. *Noncollocated* control is demonstrated using a notch filter to suppress the oscillatory plant dynamics. Similar to test series #5 in the Model 205 & 210 Experiments. See Figure 6c for tracking response.

6. Full State Feedback LQR Control. This experiment designs and implements an LQR controller for noncollocated control of the SIMO plant. Experimental results show the effectiveness of the scheme in dealing with structural flexibility. Similar to test series #6 in the Model 205 & 210 Experiments (see Figure 4). See Figure 6d for tracking response.

7. Practical Control Issues. This series of experiments addresses non-ideal conditions often present in real-world industrial plants.

a. Gear Ratio & Inertia. Shows by test and analysis the relationship between gear ratio, drive inertia, and load inertia and their affects on system gain. Demonstrates why most modern servo systems employ large gear ratios with minimal drive inertia.

b. Friction. Studies the effect of friction on steady state error and shows error reduction (for a given system bandwidth) with increased gear ratio and with noncollocated sensing when drive flexibility is present. Introduces the concept of *static servo stiffness*, and shows that this parameter becomes infinite (hence zero steady state error) when integral action is added.

c. Drive Saturation: Shows that drive saturation can lead to significant reduction in rise time, large following errors and limit cycle instability in extreme cases. (see Figure 8) Shows the effect of gear ratio on saturation and that saturation is increased when the gear ratio is either above or below some optimal value. The optimal value is obtained analytically.

d. Discrete Time Sampling: Examines the effect of sampling period, Ts, on instability and empirically obtains the maximum Ts before instability onset for low and high bandwidth systems (see Figure 8). A relationship is developed between continuous-time phase margin, crossover frequency, and sample-and-hold phase loss and is used to establish guidelines for maximum practical Ts for a given system.

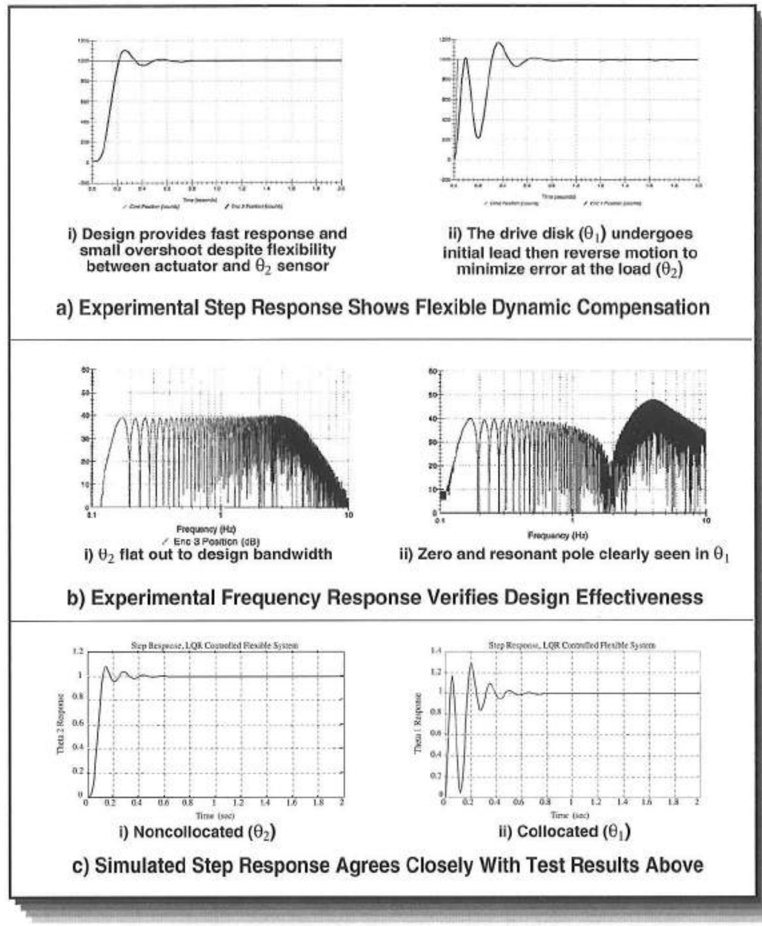


Figure 4. LQR Tests Demonstrate Effective Flexible Structure Control and Agreement of System With Dynamic Model

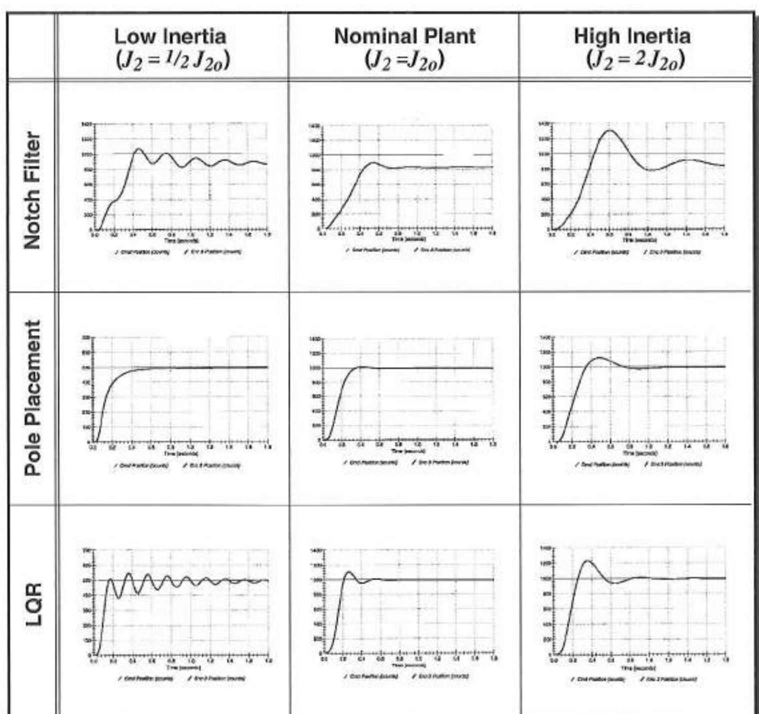


Figure 5. Robustness Tests Show Effect of Payload Changes On The Step Response of Various Control Systems

In the experiments, the frequency responses are also measured and stability margins studied

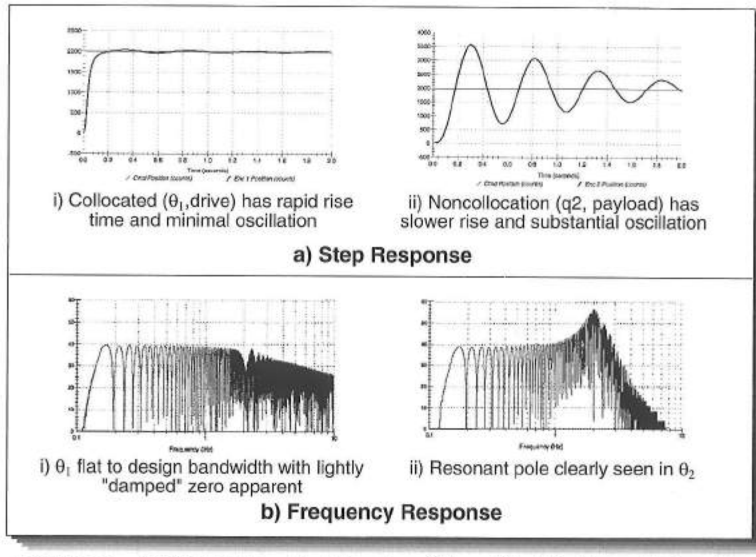
7. Practical Control Issues (contd.).

e. Sensor Quantization: Shows that with high bandwidth control terms, control effort quantization and hence noise propensity is inversely proportional to sensor resolution and Ts. This relationship is demonstrated for several control gains and sample periods.

f. Drive Flexibility: Studies various collocated and noncollocated control schemes, as described in 4 through 6 above to characterize and mitigate the effects of drive flexibility. A comparison of the various control schemes is shown in Figures 6 and 7. (see also Figures 4 and 5)

g. Backlash: Examines backlash effects in the context of collocated control in both tracking and regulation (including output disturbances). Then, implements a noncollocated scheme which significantly reduces the effect of backlash.

8. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of virtually any topic in control systems. The Model 220 apparatus is well suited to study a broad range of practical control problems. All experimental topics described on page 14 are applicable here.



i) Collocated (θ_1,drive) has rapid rise time and minimal oscillation

ii) Noncollocation (q2, payload) has slower rise and substantial oscillation

a) Step Response

i) θ_1 flat to design bandwidth with lightly "damped" zero apparent

ii) Resonant pole clearly seen in θ_2

b) Frequency Response

Figure 6. 2DOF Collocated Design Gives Well-behaved Results At The Actuator But Oscillatory Response At The Load

Model 505, ECP Inverted Pendulum Experiments

1. Plant Identification. Identifies the plant parameters, and control gains using classical techniques and uses these to construct numerical plant models for control design.

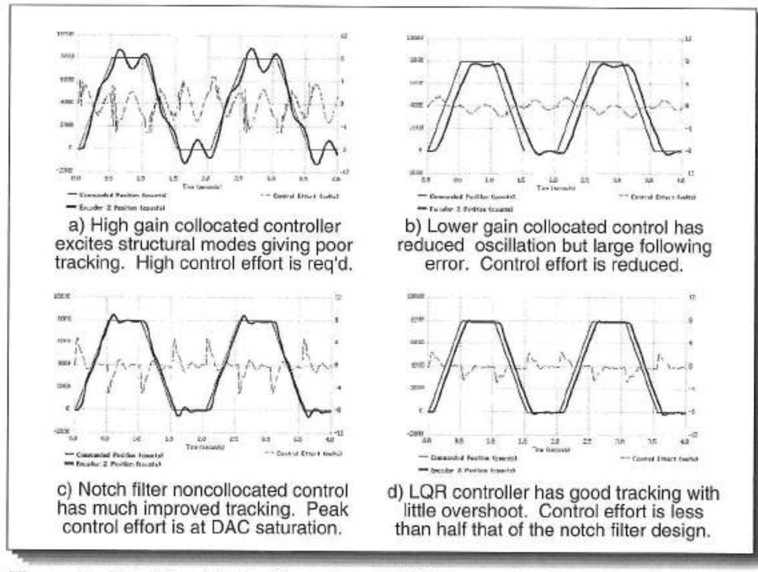
2. Successive Loop Closure Design: This experiment first implements a high bandwidth control loop about x(s)/F(s) so that x(s)/c*(s) is nearly 1 through the control bandwidth. (Here c*(s) is the control effort in the subsequent outer loop). An outer loop is designed to meet certain performance requirements for the new "plant" $\theta(s)/x(s)$. (Pole placement technique is described in the manual, other methodologies are readily supported.) Typical test data are shown in Figure 9 where the characteristic nonminimum phase undershoot is obvious in both a step and ramp following closed loop responses. This approach is implemented in cases where $\theta(s)/x(s)$ is both stable and unstable. The implications of the open loop instability and right half plane zero to stability and performance of the closed loop system are investigated.

3. Dynamic Filter Controller Augmentation: A method for augmenting control with cascaded dynamic filters is given. It is used to implement a low pass filter for noise suppression in the controllers described above.

4. LQR Control Design: LQR synthesis is employed where the states are the pendulum and balance rod positions and rates and with the error weighting exclusively on the state of the pendulum rod angle. Controllers are designed for a spectrum of control effort weights and well-behaved control of this dynamically complex system is demonstrated for a range of gains. An optional exercise involves experimental determination of gain margin.

5. Tracking Control: Various trajectories are executed on systems using the above controllers. Reduction of following error and peak control effort through use of higher order input trajectory is demonstrated. The phase and gain characteristics are studied via sine sweep responses where the extra phase lag due to the nonminimum phase zero is apparent.

6. Additional Topics: Many more experiments are readily performed. In general, those described on page 14 are applicable.



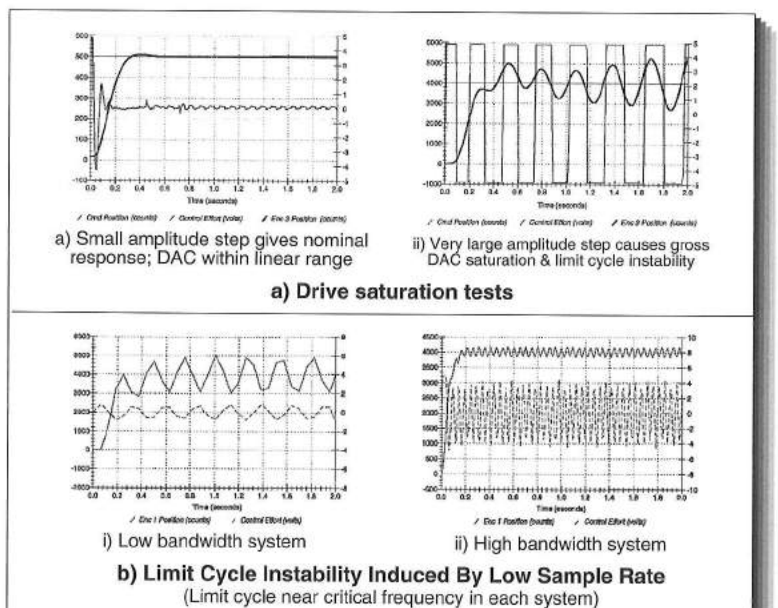
a) High gain collocated controller excites structural modes giving poor tracking. High control effort is req'd.

b) Lower gain collocated control has reduced oscillation but large following error. Control effort is reduced.

c) Notch filter noncollocated control has much improved tracking. Peak control effort is at DAC saturation.

d) LQR controller has good tracking with little overshoot. Control effort is less than half that of the notch filter design.

Figure 7. Tracking Tests Show Large Differences In System Performance



a) Small amplitude step gives nominal response; DAC within linear range

ii) Very large amplitude step causes gross DAC saturation & limit cycle instability

a) Drive saturation tests

i) Low bandwidth system

ii) High bandwidth system

b) Limit Cycle Instability Induced By Low Sample Rate
(Limit cycle near critical frequency in each system)

Figure 8. Experiments Demonstrate Important Practical Control Issues

Model 730, Magnetic Levitator Experiments

The MagLev apparatus incorporates a variety of features that let you easily perform SISO, SIMO, and MIMO experiments, on nonlinear or linearized plants in open loop stable and unstable forms and apply programmable disturbances to the SISO and MIMO configurations.

1. Plant Identification. Identifies the plant parameters, nonlinear magnetic field characteristic, and control gains and constructs numerical plant models for control design.

2. Nonlinear Plant Control: Demonstrates that the linearized model of the system is valid for small excursions about the operating point but yields anomalous behavior for large excursions. As seen in Figure 10a, the large amplitude step response is grossly asymmetric, exhibiting high gain (high damping ratio, low steady-state error) in the negative direction and low gain in the positive direction. It is shown that large negative motion can result in instability. These tests are conducted on both the open loop stable (repulsive levitation) and unstable (attractive levitation) plant configurations.

3. Nonlinear Plant Compensation: The strong nonlinearity measured in the plant identification experiments is inverted in the real-time algorithm, and a linear controller is designed for the combined linear pseudo-plant. As seen in Figure 10b, the resulting system exhibits linear response characteristics and relatively high performance.

4. Fundamentals Of Second Order Systems. These experiments and exercises utilize the nonlinear compensation routine above to effect a simple second order system. These experiments parallel those described in test series #2 in the Model 205 $ 210 Experiments (see Figure 2).

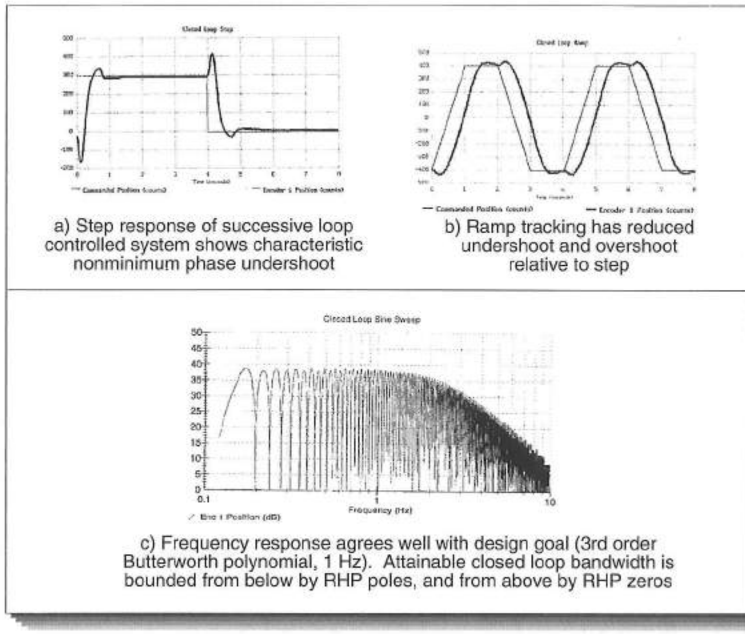
5 Disturbance Attenuation. These tests use the second actuator coil to apply disturbances to an SISO configuration with several controllers. These experiments parallel those described in test series #3 in the Model 205 $ 210 Experiments (see Figure 3).

6. Collocated SIMO Design: This experiment uses two magnets oriented in an inter-magnet repulsive configuration and implements collocated control about the first magnet. The resulting system has relatively well-behaved performance characteristics at the collocated (proximal) magnet, but is highly oscillatory at the noncollocated (distal) one. These results are similar to those seen in Figure 6.

7. Noncollocated SIMO Design For the same configuration as in #6, a successive loop, pole placement scheme is employed for noncollocated control of the second magnet. This is shown to provide tight tracking and improved disturbance rejection over the collocated approach. Step and frequency responses are similar to those of Figure 4.

8. MIMO Design These tests use two magnets and two actuators with force interaction between each magnet and both actuators and the other magnet. Independent controllers are first implemented and are shown to have significant coupling in the outputs as seen in Figure 11a. Full multivariable control synthesis is then employed which yields effective independent control of the outputs (Figure 11b). The the closed loop system is characterized via experimental singular value plots as shown in Figure 12.

9. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of virtually any topic in control systems. All experimental topics described on page 14 are applicable here.

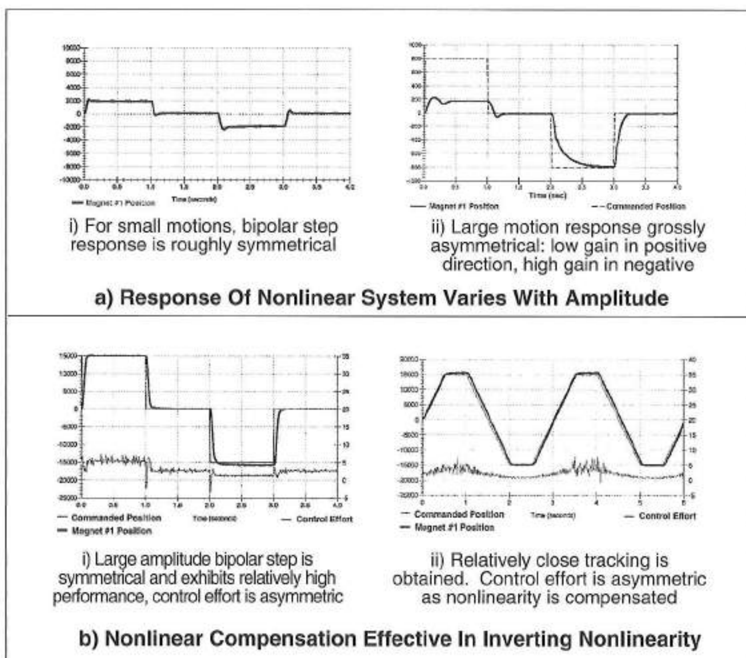


a) Step response of successive loop controlled system shows characteristic nonminimum phase undershoot

b) Ramp tracking has reduced undershoot and overshoot relative to step

c) Frequency response agrees well with design goal (3rd order Butterworth polynomial, 1 Hz). Attainable closed loop bandwidth is bounded from below by RHP poles, and from above by RHP zeros

Figure 9. Inverted Pendulum Test Results Show Nonmimimum Phase and Bandwidth Limitations Inherent In Plant



i) For small motions, bipolar step response is roughly symmetrical

ii) Large motion response grossly asymmetrical: low gain in positive direction, high gain in negative

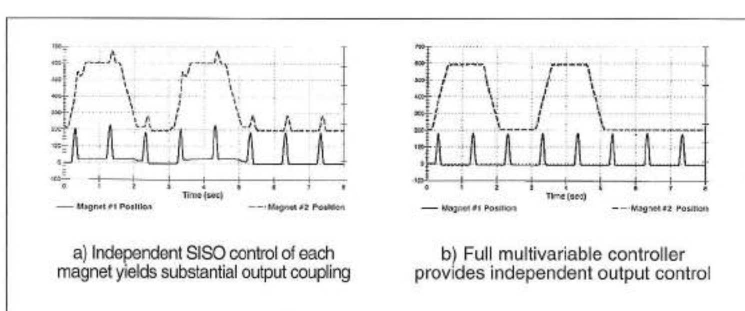
a) Response Of Nonlinear System Varies With Amplitude

i) Large amplitude bipolar step is symmetrical and exhibits relatively high performance, control effort is asymmetric

ii) Relatively close tracking is obtained. Control effort is asymmetric as nonlinearity is compensated

b) Nonlinear Compensation Effective In Inverting Nonlinearity

Figure 10. Tests Show Nonlinear Magnetic Field Characteristic and Effective Compensation



a) Independent SISO control of each magnet yields substantial output coupling

b) Full multivariable controller provides independent output control

Figure 11. MIMO Tests Show High Performance Multivariable Control

Model 750, Control Moment Gyroscope Experiments

The Control Moment Gyroscope is a dynamically rich platform that you can easily transform into a variety of linear and nonlinear SISO, SIMO, and MIMO plants, for experiments ranging from elementary to highly complex. (See Model 750 apparatus description for axis definitions used below.)

1. Plant Identification. Identifies the plant parameters through physical measurements involving conservation of angular momentum and the gyroscopic properties of nutation and precession.

2. Gyroscopic Dynamics: Nutation & Precession: Students measure the nutation frequency and mode shape at various values of angular momentum (rotor speed). The mode-shape, seen in the upper plot of Figure 13a, shows Axes 2 and 4 to be 90 deg. out of phase (unlike the more typical 180 deg.), which leads to complex eigenvectors. The nutation frequency is shown to vary linearly with angular momentum. The mode is effectively damped (lower plot in Figure 13a) by applying rate feedback at Axis 2. Precession (ω) is measured by applying a step torque input (T) transverse to the rotor momentum (H) according to the gyroscopic cross product $T = \omega x H$ (Figure 13B).

3. Reaction Torque Control: The large inertia of the rotor is used as a reactive body for control of the inner gimbal assembly about Axis 3. A typical step response, shown in Figure 14a, shows the rotor speed is the integral of control effort according to conservation of angular momentum.

4. Fundamentals Of Second Order Systems. The configuration studied in #3 behaves as a second order system about Axis 3 and therefore serves as a testbed for this important fundamental topic. These experiments parallel those described in test series #2 in the Model 205 $ 210 Experiments (see Figure 2).

5 Gyroscopic Control – Successive Loop SIMO: An inner loop controls the transverse rotor rate about Axis 2 and an outer loop controls the position of the assembly about axis 4 using using torque produced via the gyroscopic cross product. As seen in Figure 14b, the Axis 2 rate has the same shape as conventional control effort (e.g. torque) does in a rigid body system.

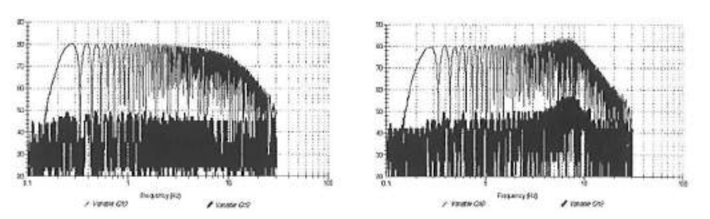
6. Gyroscopic Control – Pole Placement SISO: Control is implemented using only the Axis 4 sensor signal. The diophantine equation is solved to place the closed loop poles in a 5th order Butterworth pattern and the resulting system is characterized and shown to behave according to its design.

7. Gyroscopic Control – LQR. Full state feedback LQR methodology is utilized to produce high performance control. The three gyroscopic control methodologies are compared for various figures of merit as measured and analyzed in these tests.

8. Combined Reactive & Gyroscopic Control Axes 3 and 4 are controlled by independent reactive and gyroscopic loops. As seen in Figure 15a, this approach is shown to be effective when gimbal angles are zero (no nominal cross-coupling) but experiences gross output coupling for large off-nominal gimbal positions (Figure 15b).

9. Multi-variable Control Full multi-variable control is developed and implemented and is shown to provide largely decoupled output for large gimbal angles as seen in Figure 15b. Practical issues such as the large difference in control authority between gyroscopic and reactive actuation and the need for balancing the coupled system design are addressed.

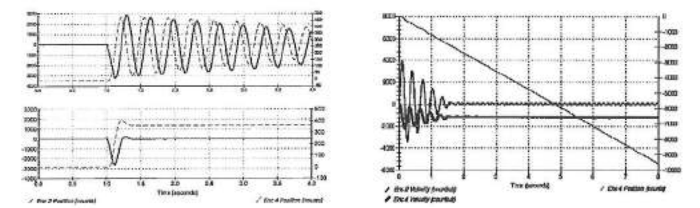
10. Any Topic You Choose! The versatility of the reconfigurable apparatus and interface software support the study of a broad range of control topics. All experimental topics described on page 14 are applicable here.



a) Sine sweep @ Input #1 shows flat response to design bandwidth in output #1 and virtually no response in output #2

b) Increased gain causes pole pair to approach imaginary axis resulting in resonance in both outputs

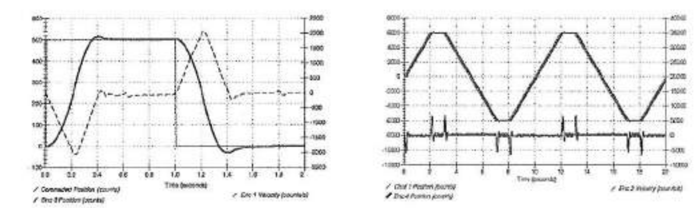
Figure 12. ECP's Experimental Singular Value Plot Function Shows Multivariable Frequency Domain Behavior



a) Upper plot: Nutation mode, 90 deg. phase between q_2 and q_4. Lower plot: effective nutation damping by q_2 rate feedback

b) Precession seen as constant slope in q_4. Transient excited by discontinuous step torque input

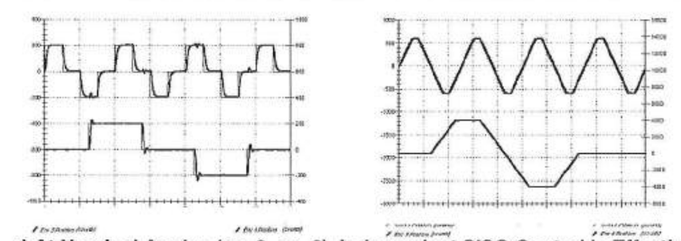
Figure 13. Dynamic Tests Show Nutation & Gyroscopic Precession



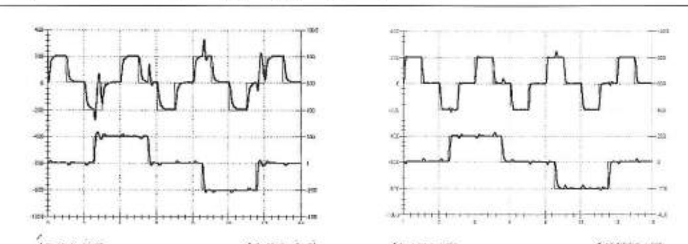
a) Reaction torque step response shows effective control of q_3, while uncontrolled rotor speed is integral of control effort

b) Gyroscopic control in ramp tracking: gimbal rate, ω_2 seen to act same as conventional control effort

Figure 14. SISO Data From Reactive & Gyroscopic Control Experiments Show Characteristic Properties



a) At Nominal Angles (q_2=0, q_3=0), Independent SISO Control Is Effective



i) Gross output coupling in independent SISO controlled system

ii) Multivariable control yields small output coupling

b) At Off-nominal Gimbal Angles (q_2=30°, q_3=30°), Multivariable Control Required To Minimize Output Coupling

Figure 15. MIMO Plant Tests Show Need For Multivariable Controller

Accessory 51 Experiments

The Accessory 51 Classical pendulum includes the following detailed experiments and solutions. Matlab™ scripts are provided for all analysis and control design elements and controller code is given for implementation via the ECP Executive USR™ program. The experiments below are included for each base unit type (models 205, 210, 220, and 750).

1. Numerical plant model generation. Generates the plant models as a function of user adjustable parameters such as rod length and mass position. Builds the inverted and non inverted plants in transfer function and state space forms.

2. LQR Inverted Pendulum Control. Designs, implements and tests full state feedback LQR controllers with various control weights. The controllers track reference inputs while maintaining system stability (balancing the pendulum). The sine sweep (frequency) and transient step responses are obtained.

3. Self-inverting algorithm. Provides algorithm for the plant to automatically invert the pendulum. The routine pumps energy into the pendulum at properly phased instants until the it reaches the inverted neighborhood where the system transitions into inverted control.

4. Non-inverted control. Performs LQR synthesis for the pendulum in the non-inverted configuration and obtains the frequency and transient responses to characterize then system. It is seen that there are limitations in the ability to provide both high bandwidth base response and damped pendulum motion.

5. Pole Placement Control. Performs pole placement synthesis and implements and characterizes the design. The designs generally show performance limitations relative to the LQR-based ones for the parameters selected.

6. Control Robustness: The pendulum mass is moved from its nominal location and the limits of stability for the increased and decreased positions are found empirically as the onset of unstable oscillations.

Further Study & Experiments

With ECP's multi-use mechanisms and flexible real-time processing, you can study virtually any control topic you wish! Selected examples are given below.

1. System Identification. In addition to the classical approaches provided in ECP manuals, global techniques such as least squares estimation may be employed.

2. Plant Dynamics. Additional topics in plant dynamics may be studied such as modeshapes, natural frequencies, free and transient response, harmonic response, system type, assymptotic properties, etc. These are facilitated in the Model 205 & 210 systems via the optional Dynamics & vibrations software & experiments package.

3. Sensitivity & Robustness. While for most of our systems, this topic is studied in the provided experiments in the context of inertia changes, sensitivity and robustness to other parameters (e.g. spring constant, damping constants, individual sensor gain, etc.) are also readily tested.

4. Advanced Control. Using the *ECP Executive*™'s library of control forms virtually any linear controller up to and including up to ninth order may be implemented and characterized. Examples include *Observer/controller based, LQR/LTR, H∞, μ -synthesis*, and *QFT*. With the optional *ECP Executive USR*™ package, you can implement virtually any control scheme imaginable including *fuzzy logic, nonlinear, adaptive,* and *variable structure.*

5. Feedforward Tracking Control. The *ECP Executive*™ provides up to seventh order feed-forward capability for augmentation of any controller. Thus feedforward tracking control may be studied and performance optimized.

6. **Optimal Trajectory Generation:** Use the library of trajectories or implement your own arbitrary shapes to establish reference input paths for minimized error, control effort, or execution time.

7. **Practical Control Implementation:** The majority of the practical control study topics provided with Models 205, 210, and 220 may be applied to the remaining systems.

8 **And Much More!** The only limitation is your imagination!

Executive Program

The *ECP Executive*™ Program

The *ECP Executive*" program is intuitively easy to use yet powerful enough to implement virtually any linear controller. Advanced trajectory generation and plotting features let you efficiently determine system performance and stability. The program has the menu structure shown in Figure 16. It includes a full library of continuous and discrete time control forms plus a building-block generalized algorithm (Figure 17) that let you rapidly implement controllers of up to 48 terms. Flexible trajectory generation, data acquisition, and plotting features let you quickly determine frequency response, transient response, stability margins, disturbance rejection, and dynamic tracking behavior

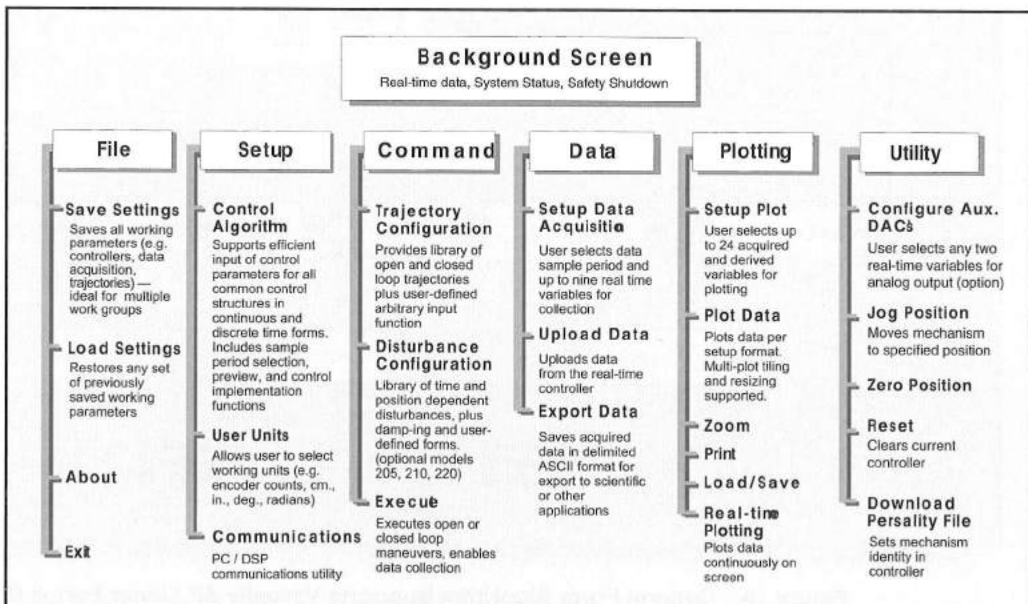
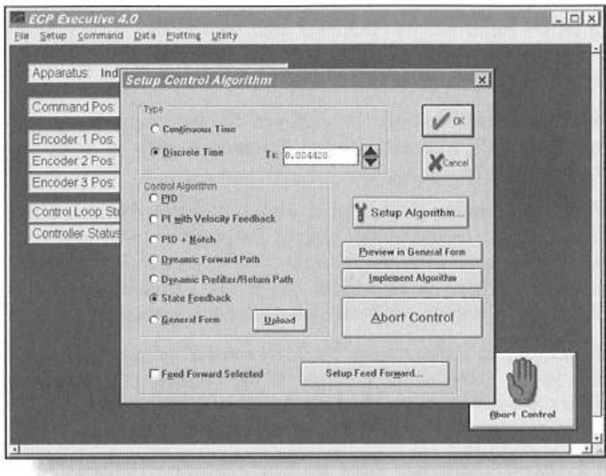


Figure 16. Executive Program Menu Structure Is Full-Featured & Easy To Use

Executive Program

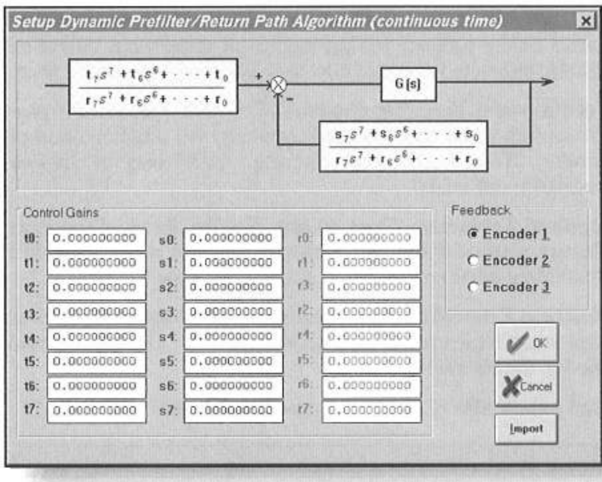


Background Screen

- Provides real-time display of: reference input command, control effort, feedback sensor positions, and system health status
- Provides for rapid safety shutdown

Controller Type Selection

- Library of common forms to select from
- All controllers may be entered in continuous or discrete-time form
- Sample period variable from 0.8 ms to arbitrarily long
- Feedforward may be augmented to any controller



Controller Specification

(Typical controller specification window shown)

- Shown is one in library of common forms:
  - PID
  - State feedback
  - Cascade forms
  - Selection of ARMA/dynamic filters
  - Over 20 available forms
- Import control parameters from other applications such as Matlab®
- Specify any controller in either continuous or discrete time forms
- All forms mapped into the generalized form (Figure 17) for real-time execution via the DSP board

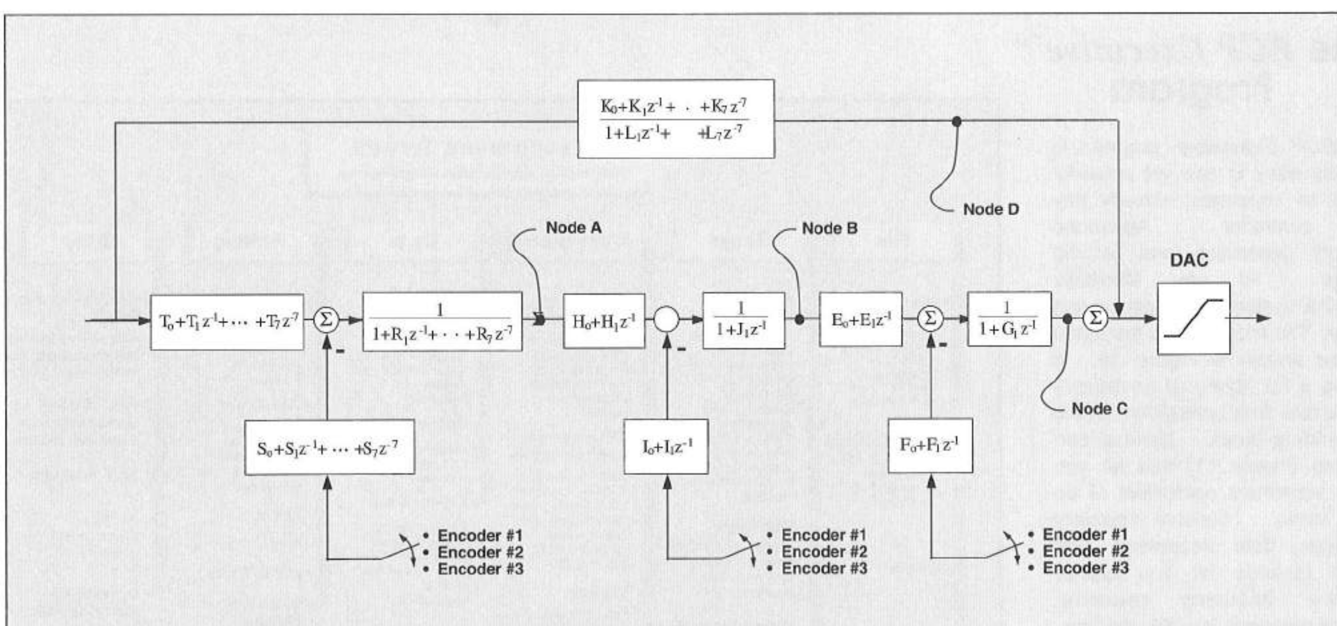
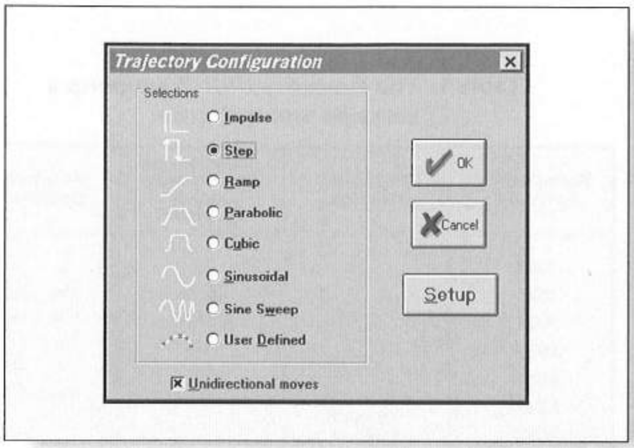


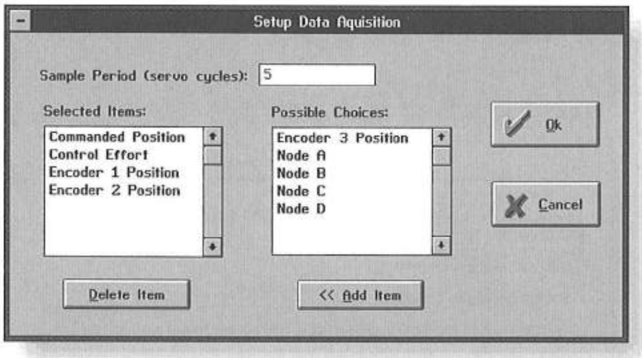
Figure 16. General Form Algorithm Supports Virtually All Linear Forms OF Up to 45 Terms
Hardware performs this real-time algorithm at specifiable rates up to 1.1 kHz with 96 bit precision.

Executive Program



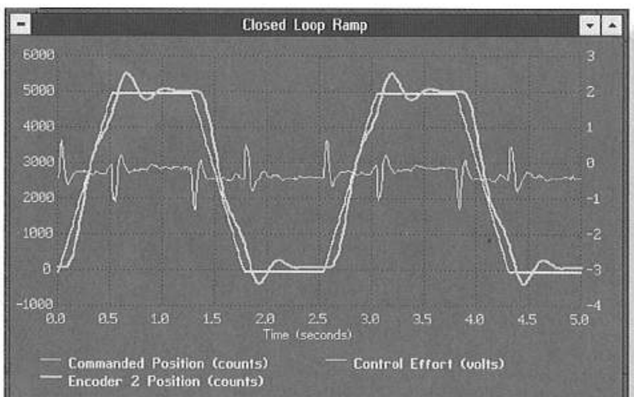
Input Trajectory Generation

- Library of geometric and sinusoidal inputs:
  - Impulse
  - Step
  - Ramp
  - Parabolic
  - Cubic
  - Sinusoid
  - Sine sweep (frequency response input)
- User defined trajectory w/ max of 4000 data points @ up to 1.1 kHz



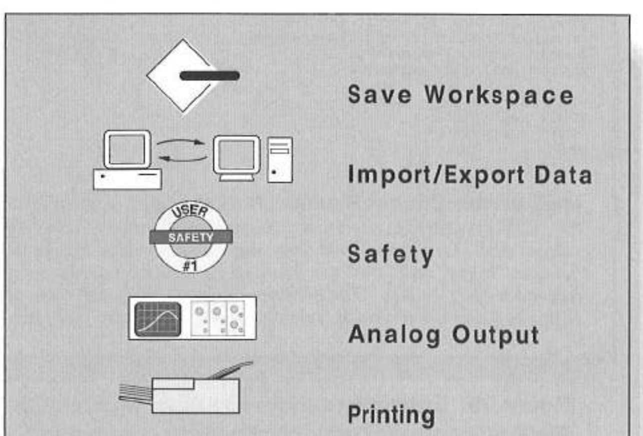
Data Acquisition

- Select any or all of nine unique dynamic variables
  - Up to 4 feedback sensor positions
  - Reference input trajectories
  - Control effort
  - 4 controller-internal states
- Calculates time derivatives & differences of acquired data to provide up to 20 variables for plotting
- Data acquired at specifiable rates up to 1.1 kHz & up to 16,000 data points per variable.



Plotting

- Choose any acquired or derived data for plotting
- Up to 4 variables plotted simultaneously
- On-screen, real-time plotting
- Two independent y-axis scalings
- Zoom feature for detailed data inspection
- Save plots for subsequent retrieval
- On-screen features: multiple plots, resizing, shink-to-icon & restore



Utility & Safety

- Save all working parameters to facilitate multiple work sessions or users (e.g. student work groups)
- Imports or exports data to other applications
- Safety: Travel limit, over-speed, motor/amplifier over -heat plus hardware & software emergency shutdown.
- Two programmable analog outputs for real-time data monitoring (optional)
- Prints plots directly to printer

Executive USR Program

The ECP *Executive USR*™

The *Executive USR*™ allows you to efficiently implement virtually any control form imaginable from simple low order SISO, to complex nonlinear MIMO. It provides a built-in editor and auto-compiler that lets you easily write your algorithm and implement it — all within the same intuitive environment. It also incorporates the many powerful trajectory generation, data acquisition, and plotting features of the basic *Executive* program.

With the *Executive USR* you can . . .

1. **Write your own fully general control forms** including advanced schemes such as nonlinear, adaptive, fuzzy logic, and variable structure.

2. **Use the built-in editor and auto-compiler** to immediately generate, compile, download, and implement your real-time design.

3. **Utilize a powerful, intuitive language** that supports all common arithmetic, logical, and relational operators, and exponential and transcendental functions.

4. **Exercise more complete system control** with all pertinent variables and I/O directly addressable.

5. **Employ high performance real-time execution** using the computationally efficient compiler and high-speed DSP. These combine to provide high throughput performance, allowing you to implement complex routines with execution rates of up to 1.1kHz.

6. **Implement MIMO Control** on ECP Models 205, 210, and 220 (MIMO is standard on models 730 and 750) when combined with the optional second drive accessory.

7. **Enjoy all other useful features of the basic *Executive"*** program such as advanced trajectory, data acquisition, plotting, safety, and utility functions.

The instruction set supported by the Executive USR" is shown in Table 1. An example routine is shown in Figure 19, which demonstrates the intuitive program syntax and flow.

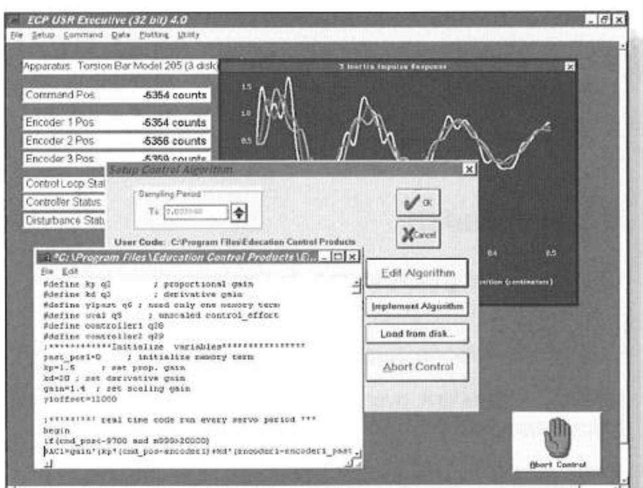


Figure 18. The *Executive USR*™ incorporates a built-in algorithm editor and autocompiler with the other advanced features of the standard *Executive*™

Table 1. The *Executive USR*™ supports a versatile instruction set

Mathematical Functions*	Arithmetic Operators	Conditional Statements / Logical Operators	Relational Operators
SIN	+	IF	= (=)
COS	-	ELSE	!= (≠)
TAN	*	ENDIF	> (>)
ASIN	/	AND	!> (≤)
ACOS		OR	< (<)
ATAN			!< (≥)
SQRT	the usual parenthetic grouping and precedence rules apply		
LN			
EXP			
ABS			
INT			

```
;*************** Declare variables **************
#define Ts q5
#define y1str q6
#define comp_effort1 q7
...
Continue Declaring Variables

;****************** Initialize ******************
Ts=0.001768
u1o=18000 ;gravity/control effort offset
u2o=5800 ;gravity/control effort offset
y1o=10000
y2o=-20000
k11=1.7
k12=0.064
k13=0.15
k14=.003
k21=.15
k22=.003
...
k12d=0.064/Ts
...
Continue Initializing

;************ Begin Real-time Algorithm ***********
begin
magnet1_pos=sqrt(210000/sensor1)+0.15*sensor1-28000  } Sensor
magnet2_pos=sqrt(225000/sensor2)+0.14*sensor1-24500  } Calibration/
y1str=magnet1_pos-y1o                                } Linearization
y2str=magnet2_pos-y2o
delta_y1=y1str-y1str_last
delta_y2=y2str-y2str_last

;LQR ALGORITHM                          Linear Multivariable Controller
u1str=kpf1*cmd1_pos-k11*y1str-k12d*delta_y1-k13*y2str-k14d*delta_y2
u2str=kpf2*cmd2_pos-k21*y1str-k22d*delta_y1-k23*y2str-k24d*delta_y2

;OUTPUT
u1=u1str+u1o
u2=u2str+u2o
ucomp1=0.000165*6.2+exp(4.1*ln(magnet1_pos/10000))  } Magnetic Field
ucomp2=0.000165*6.2+exp(4.1*ln(magnet1_pos/10000))  } Nonlinearity
control_effort1=ucomp1*u1                           } Compensation
control_effort2=ucomp2*u2

;UPDATE (for next time)
y1str_last=y1str
y2str_last=y2str
end
```

Multivariable Control Routine *The user-written routine follows the USR program flow format: 1) declare variables, 2) initialize values, and 3) execute real-time algorithm. Only the portion between "begin" and "end" are executed at the user selected sample frequency (1Hz-1KHz). The nonlinear compensation functions and LQR controller are written in a straightforward language and syntax.*

Figure 19. Example real-time routine: Multivariable MagLev controller with nonlinearity compensation

Interface Solutions

The ECP Executive™

A powerful, easy-to-use system interface

ECP's Executive interface program provides a rich set of features that help you efficiently implement control and characterize the frequency and time domain behavior of your design. It has high fidelity data acquisition and plotting functions to quickly assess system performance and stability. Workspace and configuration save functions are ideal for multiple student study groups. The program is optimized for ECP's high speed DSP board in performing real-time control and trajectory generation within the turn-key ECP architecture.

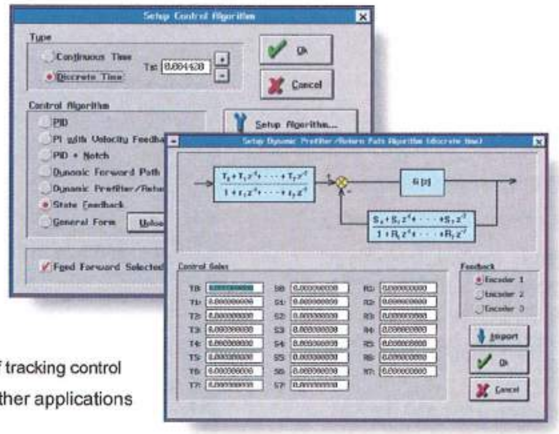
Background Display

Gives real-time data & system status at a glance

- View real-time time data graphically & numerically
- See system health and control status at a glance
- Perform instant safety shutdown

Controller Setup

Efficiently implements a broad range of control designs

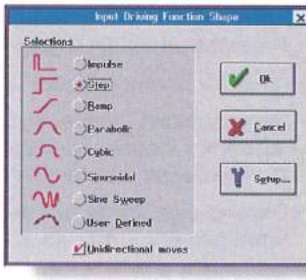


- Quickly specify your controller using any of 15 forms
- Select sample rates from 0 to 1.1 kHz
- Input controller designs in discrete or continuous time forms
- Construct your own linear form of up to 35 terms (96 bit precision)
- Apply feedforward filters for study of tracking control
- Import your control design from other applications such as Matlab™

Input Trajectory Commanding

Rapidly tests transient & frequency responses

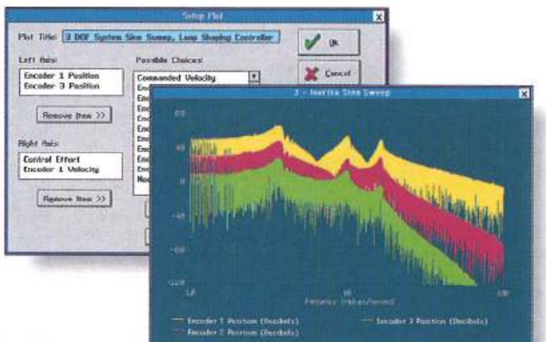
- Select from library of 14 shapes plus user-defined forms
- Characterize transient response using geometric inputs
- Determine frequency response using ECP's sinusoidal and sine sweep functions
- Apply complete shape control on library forms or create your own!



Data Acquisition & Plotting

Helps quickly visualize system behavior

- Acquire up to 10 system states simultaneously at up to 1.1 K Hz
- View on-screen real-time plotting
- Plot any of up to 21 variables and derived values
- Use ECP's unique Bode magnitude function to view experimental frequency responses
- Export data for off-line manipulation and analysis



Workspace, Safety, & Utility Functions

Assure efficient, trouble-free operation

- Save all working parameters to efficiently resume at later time - ideal for multiple student work groups
- Rest assured with built-in safety limits for mechanism over-speed, over-travel, and motor / amplifier overheat protection
- Perform utility functions such as resetting controller, commanding system to fixed position, and setting engineering data units

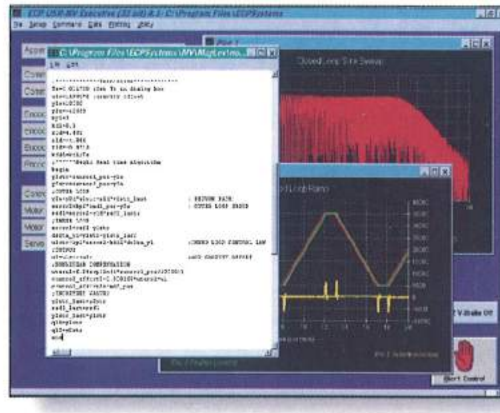
Which Solution is Best For Me?

	Environment	Integration	Availability
ECP Executive™	Intuitive controller libraries, trajectories, data acquisition, & plotting	Turn-key	Standard on Models 205, 210, 220, and 505 (Complete systems)
ECP Executive DYN™	Intuitive menu-driven program for study of dynamics & vibrations - no controls experience necessary	Turn-key	Optional for models 205 and 210
ECP Executive USR™	Same as basic Executive except implement virtually any controller via user-written algorithms	Turn-key	Standard on system Models 730 and 750, optional on all other models
ECP Extension to RTWT™	Simulink block diagrams	ECP turn-key system plus Mathworks RTWT, RT Workshop, MATLAB, and Simulink	Optional for all models (complete systems only)
Plant Only	User selected	Third party control hardware and software (e.g. via LabView, D-Space or other user choice)	Optional for all mechanism models

Interface Solutions

ECP Executive USR™

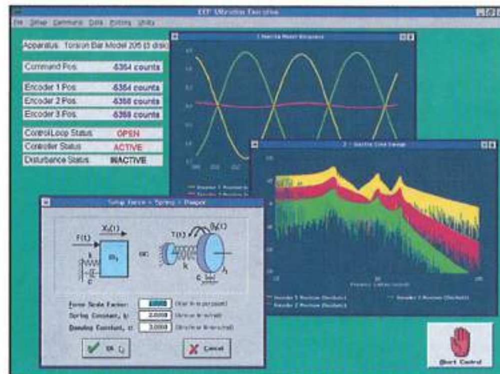
For User-Written control structures



- Efficiently implements virtually any control form
- Provides all other features of the basic Executive™ program plus multi input functionality
- Supports Intuitive C-like language with all common arithmetic and logical operators, exponential and transcendental functions
- Provides built-in auto-compiler to immediately compile, download, and implement your real-time design
- Gives you more complete control of the system with all system I/O and necessary internal data directly addressable

ECP Executive DYN™

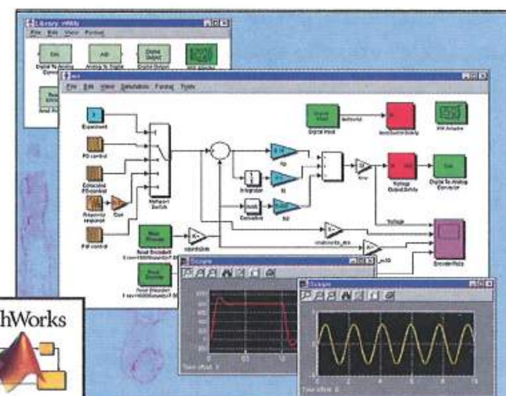
Dynamics and vibrations experiments made simple



- Provides an intuitive graphic interface for study of dynamics and vibrations
- Ideal for undergraduate courses with no prerequisite controls course work
- Demonstrates, fundamentals of second order systems, forced harmonic response, transient response, convolution, superposition, higher order mode shapes and frequencies, base motion excitation, and much more
- Easy-to-use library of input forcing functions plus all the plotting and data management functions of the ECP Executive program
- Includes a complete set of dynamics experiments and instructor solutions

ECP Extension to RTWT™

For operation in a real-time Simulink® environment

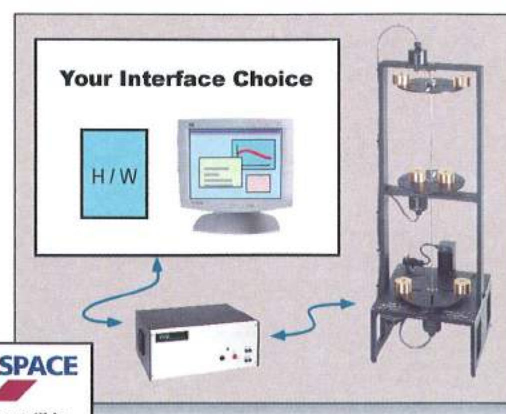


MathWorks Partner

- Lets you operate any ECP system in a Simulink block diagram environment
- Integrates fully with ECP turn-key systems - no additional hardware required
- Lets you analyze, design, and simulate the system, and implement real-time control from the same host using Matlab / Simulink
- Requires from Mathworks: Real-time Windows Target, Real-time Workshop, MATLAB, and Simulink.
- Provides dual use: quick start using turn-key ECP Executive or Executive USR, than add real-time Simulink functionality for specialized study

"Plant Only" Configurations

Complete flexibility for user integration



dSPACE Compatible

- Allows you to control the plant with the hardware and software of your choice (e.g. D-Space, Delta Tau, ServoToGo, other DSP or data acquisition/PC solutions)
- Includes mechanism, drive box with servo amplifier(s) and power supply(s), same experiments as with complete systems (some may not apply)
- Interfaces: Control effort 0-10V analog, Encoder feedback A-quad-B (0-5 V TTL), analog feedback (model 730) 0-10V bipolar, Limit switch signals (where applicable)
- Does not include DSP board, interface software, DSP interface electronics

Thought-provoking Experiments

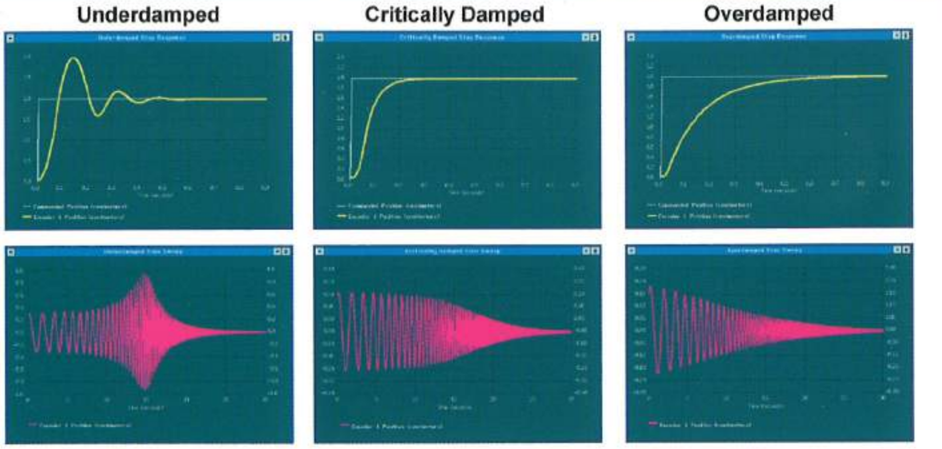
. . . that bridge the gap between theory and real-world applications

A full set of experiments are provided with each system. Detailed instructions for the students and complete solutions for the instructor greatly reduce your time in class preparation, laboratory supervision, and assignment grading. Additional features such as summary review sections, Matlab® design and analysis scripts, and instructor-optional assignments let you tailor the course to your curriculum needs.

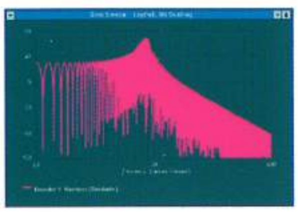
Underdamped | Critically Damped | Overdamped

Step Response

Frequency Response



Log(ω)/dB Response



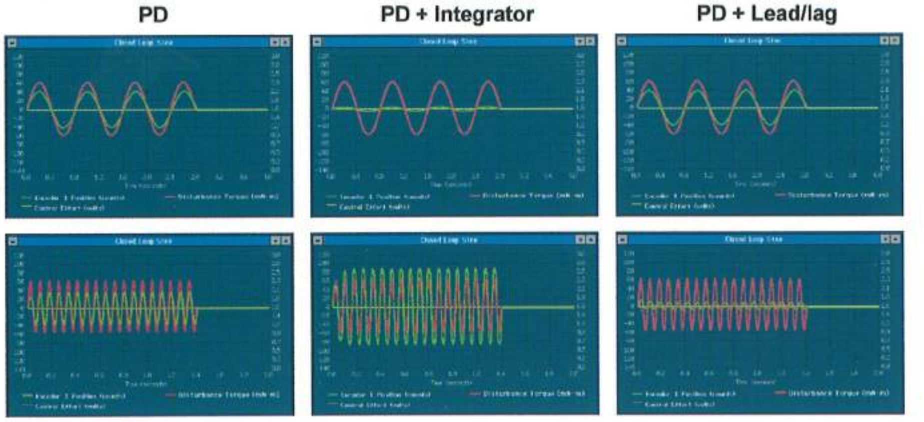
PID Experiments Examine Fundamental Properties

Here students literally get a "feel" for the distinct proportional, derivative, and integral actions by implementing them and physically manipulating the plant. They then design and test, the under-, critical-, and overdamped systems and obtain the step and sine sweep (frequency) responses. The sine sweep data are plotted above using linear scaling and then ECP's dB amplitude / log-frequency to provide an intuitive interpretation of classical Bode magnitude. Further tests examine the characteristic S- plane roots, effect of various parameters on ω_n & ζ and phase & gain margins, and correlation of time and frequency domain behavior.

PD | PD + Integrator | PD + Lead/lag

Low Freq. Disturbance

High Freq. Disturbance



Disturbance Attenuation & Control Effectiveness

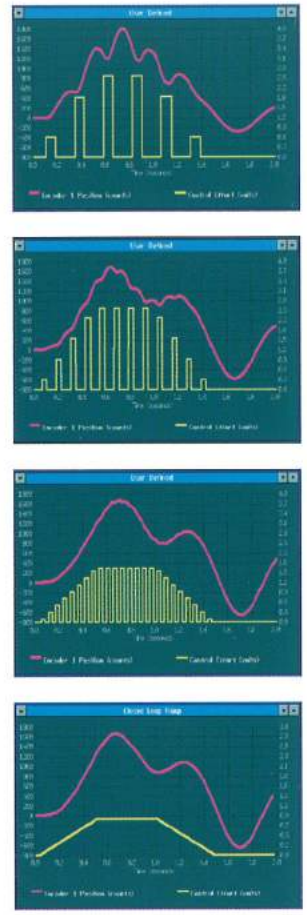
Disturbance Force

Output Position

Reference Input

The student designs a simple PD controller for a second order plant with augmenting integral action and a lead/lag filter. Tests show the PD controller provides moderate attenuation of both low and high frequency disturbances. With the added integrator, the low frequency disturbance is highly attenuated, but the high frequency one is amplified. The lead/lag filter has little effect at low frequency but is effective at high frequency. The student learns that the effectiveness of control regulation depends on the controller gain characteristic and the frequency of the disturbance itself.

Revealing Demonstration Of Linear System Properties

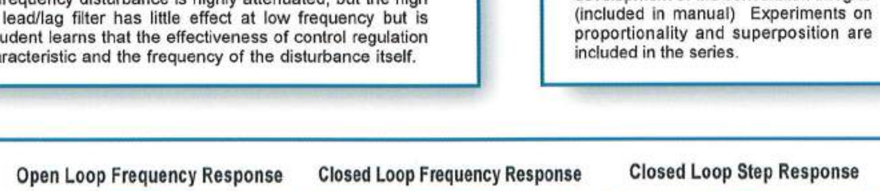


This unique ECP experiment demonstrates the linear system properties of proportionality, superposition, & convolution. The system impulse signature is first measured, then an arbitrary continuous input function is approximated by a series of discrete impulses. As the series resolution becomes fine, the output approaches that from the continuous input. Thus the experiment parallels the classical theoretical development of the convolution integral (included in manual) Experiments on proportionality and superposition are included in the series.

Practical Approaches To Control Of Flexible Structures

These experiments study effective approaches for control of plants with structural flexibility. Shown are the empirical Bode magnitudes of the open and closed loop systems where the primary control output is distant from the actuator (noncollocated). As seen in the middle plot, the output (green) is well flattened by the control. Important properties of high order systems are seen in the poles, zeros, and gain slopes in these graphs. In the closed loop step response, the collocated inertia moves "wildly" to provide a well-behaved response at the noncollocation

Open Loop Frequency Response | Closed Loop Frequency Response | Closed Loop Step Response



Satisfied Customers . . .

ECP has refined its systems through years of technology development and feedback from our customers. Here's what just a few are saying:

Dr. Robert H. Bishop, University of Texas at Austin

"We have used ECP's Torsion/Disk and Inverted Pendulum Plants as classroom demonstration tools for several years. This year we will offer for the first time a new control laboratory course. We selected ECP's models 205 and 210 because they have proven to be very reliable teaching platforms with clean dynamic properties. This has allowed us to efficiently build the laboratory course in a short time."

Dr. Randy Freeman, Northwestern University

"After 10 years of steady use of our 5 ECP Torsion/Disk Model 205 systems, we had their power electronic boxes upgraded by ECP last year to work with our new real-time controllers. These systems have yet to give us any problems in 11 years of operation. Their dynamic behavior relative to the equivalent theoretical models has been impressive. This year we decided to purchase 5 more ECP Magnetic Levitation (Model 730) systems as examples of MIMO nonlinear control plants. So far, we have found the Model 730 to be interesting and up to our expectations."

Dr. Ron Hirschorn, Queen's University, Ontario

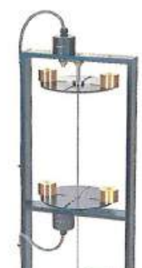
"We have been impressed with the durability and dynamic quality of the ECP system. This has enabled efficient implementation of a range of control experiments such as system identification, LQR, LQG, and sliding mode control. Agreement with analytical predictions has been excellent."

Dr. Gregory Plett, University of Colorado, Colorado Springs

". . . this device provides dramatic and interesting demonstrations. The actuators and sensors are clean, high-quality devices, and the entire system is ruggedly constructed. This device is especially well-suited to demonstrate analysis and design techniques taught in classical . . . and modern analog and digital control." (reference to ECP Model 730 MagLev system

Turn-key Systems*
That Setup in Minutes

- Multi-use, reconfigurable apparatus
- High speed DSP board
- Student manual with detailed experiments
- Instructor manual with complete solutions



- Executive™ Interface software
- Real-time firmware
- I/O electronics (servo amplifiers, power supplies)
- Quick-connect cabling
- And more!

With our user-friendly interface software, plug-in hardware connections and quick start control examples, you can perform meaningful experiments within minutes of opening the box!

***"Plant Only" options also available. See descriptions in this catalog**

From Leading Institutions World-wide

Since delivery of our first products in 1991, ECP's equipment has received broad acceptance in the academic and industrial training markets. We have now supplied equipment and services to over 400 colleges, universities and industrial sites. Our satisfied customers hail from a variety of world class institutions such as those listed below. Won't you join them in enjoying the many benefits that our systems provide?

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Case Western University
Clemson University
Johns Hopkins University
Naval Postgraduate School
North Carolina State University
Northwestern University
Purdue University
Rice University
Stanford University
State University of New York - Stonybrook, New Paltz
Texas A&M University
University of Arizona
University of California - Berkely, Los Angeles, Irvine, San Diego, Davis, Riverside
University of Colorado
University of Florida - Northern Florida, Central Florida
University of Illinois - Urbana, Chicago
University of Massachusetts
University of Michigan - Ann Arbor, Dearborn
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