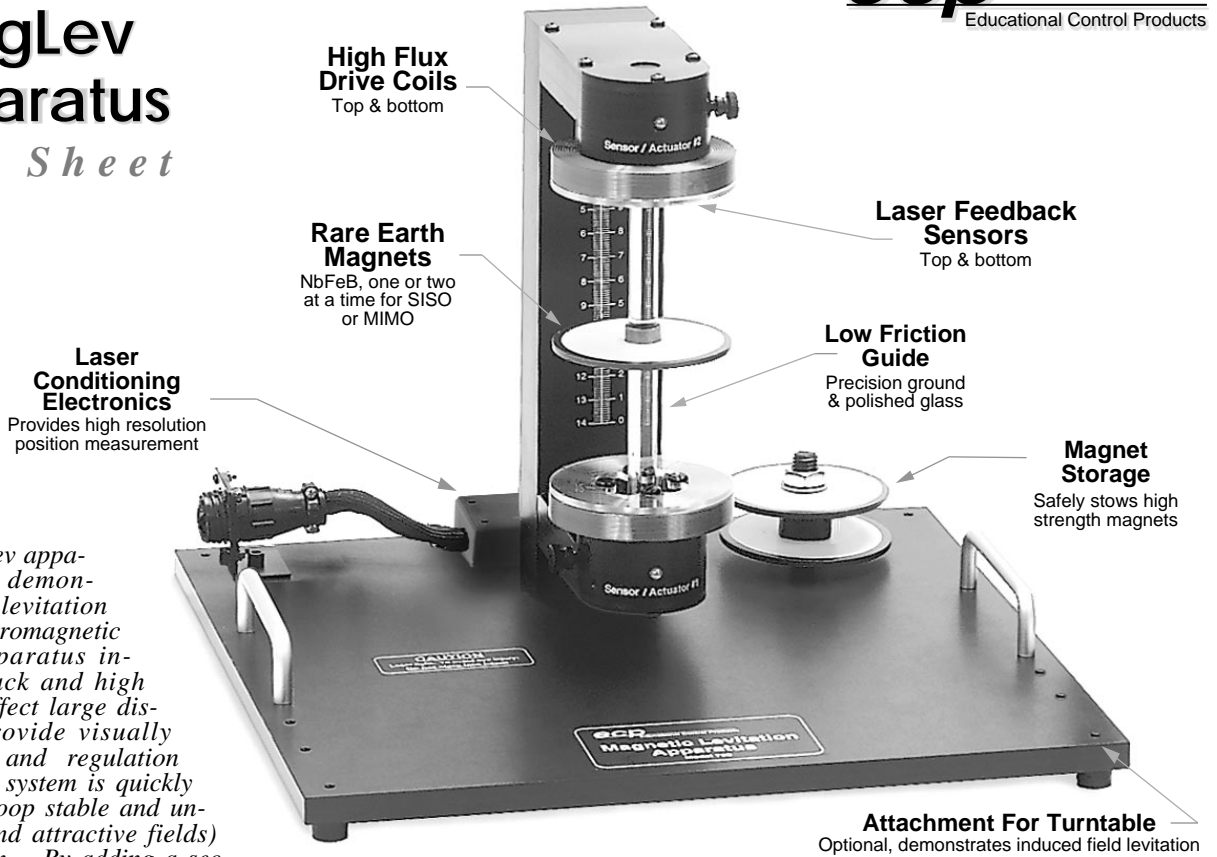


# Model 730 MagLev Apparatus

## Fact Sheet



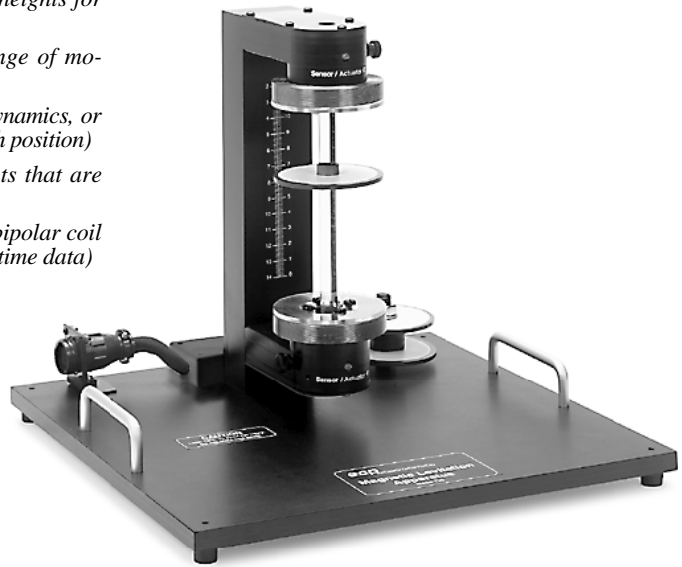
ECP's unique MagLev apparatus dramatically demonstrates closed loop levitation of permanent and ferromagnetic elements. The apparatus includes laser feedback and high flux magnetics to affect large displacements and provide visually stimulating tracking and regulation demonstrations. The system is quickly set up in the open loop stable and unstable (repulsive and attractive fields) configurations shown. By adding a second magnet and driving both actuators, 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. An optional turntable accessory provides graphic demonstration of induced field levitation - the principal used in high speed bullet trains!

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

Configuration	Diagram 1	Diagram 2	Diagram 3	Diagram 4
	<p>Repulsive Levitation Open Loop Stable</p>	<p>Attractive Levitation Open Loop Unstable</p>	<p>MIMO Levitation, Locally Open Loop Stable</p>	<p>MIMO Levitation, Open Loop Unstable</p>
Equations of Motion	$m\ddot{y} + c\dot{y} = F_{c_1 m} - mg$ <p>(<i>c</i> is very small friction modeled as viscous)</p>	$m\ddot{y} + c\dot{y} = F_{c_2 m} - mg$	$m_1\ddot{y}_1 + c\dot{y}_1 = F_{c_1 m_1} + F_{m_1 m_2} + F_{c_2 m_1} + m_1 g$ $m_2\ddot{y}_2 + c\dot{y}_2 = F_{c_1 m_2} + F_{m_1 m_2} + F_{c_2 m_2} + m_2 g$	$m_1\ddot{y}_1 + c\dot{y}_1 = F_{c_1 m_1} - F_{m_1 m_2} + F_{c_2 m_1} + m_1 g$ $m_2\ddot{y}_2 + c\dot{y}_2 = F_{c_1 m_2} - F_{m_1 m_2} + F_{c_2 m_2} + m_2 g$
Linearized Forms (about some coil current / gravity equilibrium)	$m\ddot{y}' + c\dot{y}' + ky' = k_F I_c'$	$m\ddot{y}' + c\dot{y}' - ky' = k_F I_c'$	$m_1\ddot{y}_1' + c\dot{y}_1' + (k_1 + k_2 - k_3)y_1' - k_2 y_2' = k_{F_1} I_{c_1}' + k_{F_{21}} I_{c_2}'$ $m_2\ddot{y}_2' + c\dot{y}_2' + (k_2 - k_4 + k_5)y_2' - k_2 y_1' = k_{F_2} I_{c_1}' + k_{F_{22}} I_{c_2}'$ <p>Stable <math>\forall (k_1 + k_2) \leq k_3</math> and <math>(k_2 + k_5) \leq k_4</math></p>	$m_1\ddot{y}_1' + c\dot{y}_1' + (k_1 - k_2 - k_3)y_1' + k_2 y_2' = k_{F_1} I_{c_1}' + k_{F_{21}} I_{c_2}'$ $m_2\ddot{y}_2' + c\dot{y}_2' - (k_2 + k_4 - k_5)y_2' + k_2 y_1' = k_{F_2} I_{c_1}' + k_{F_{22}} I_{c_2}'$ <p>Stable <math>\forall k_1 \geq (k_2 + k_3)</math> and <math>k_5 \geq (k_2 + k_4)</math></p>
Transfer Function (selected linearized plant)	$\frac{Y}{I_c} = \frac{k_F}{ms^2 + cs + k}$ <p>TF of above left stable system</p>		$\begin{bmatrix} m_1 s^2 + cs + (k_1 + k_2 - k_3) & -k_2 \\ -k_2 & m_2 s^2 + cs + (k_2 + k_5 - k_4) \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} k_{F_1} & k_{F_{21}} \\ k_{F_{21}} & k_{F_2} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$ <p>TF of above left system; stability assumed</p>	
Notation	$F_{c_1 m} = \frac{k_{cm} I_c}{(y+d)^{N_{cm}}}, \quad F_{c_2 m} = \frac{k_{cm} I_c}{(d-y)^{N_{cm}}}$ <p>"<i>r</i>" denotes value relative to some equilibrium pt. <math>k_{cm}</math>, <i>d</i>, &amp; <math>N_{cm}</math> are positive constants, (<math>N_{cm} \approx 4</math>)</p>		$F_{c_1 m_1} = \frac{k_{cm} I_{c_1}}{(y_1 + d_{c_1 m_1})^{N_{cm}}}, \quad F_{m_1 m_2} = \frac{k_{nm}}{(y_1 - y_2 + d_{m_1 m_2})^{N_{nm}}}, \quad F_{c_2 m_1} = \frac{k_{cm} I_{c_2}}{(y_1 + d_{c_2 m_1})^{N_{cm}}}$ $F_{c_1 m_2} = \frac{-k_{cm} I_{c_1}}{(y_2 - d_{c_1 m_2})^{N_{cm}}}, \quad F_{c_2 m_2} = \frac{-k_{cm} I_{c_2}}{(y_2 - d_{c_2 m_2})^{N_{cm}}}$ <p>Notation similar to that for SISO (<math>N_{nm} \approx 4</math>)</p>	

## Advanced System Features, Time-saving Benefits

- Rare earth magnets with ultra high flux density produce large levitation heights for graphic trajectory tracking demonstrations
- Precision non-contacting laser sensors provide feedback over large range of motion without introducing friction
- System may be operated over limited range to demonstrate linear system dynamics, or over large range to show inherent high nonlinearity (inverse fourth order with position)
- Magnets are easily added and removed to provide MIMO or SISO plants that are open loop stable or unstable
- Adjustable scale for mechanical height reference and dual color LED for bipolar coil current indication promote visualization of system states (available in real-time data)
- Durable plate and bar aluminum construction (guide rod is fracture resistant Pyrex®), and ruggedized industrial grade electronics assure highly reliable operation
- Step-by-step instructions, intuitive interface software, and detailed experiments with solutions assure productive use of laboratory time.
- Safety features such as amplifier thermal dissipation limit, over-current shutdown, and magnet overspeed protection assure equipment durability and a safe operating environment
- Bench top sized with quick connect cabling for easy transportability and reconnection to rest of system

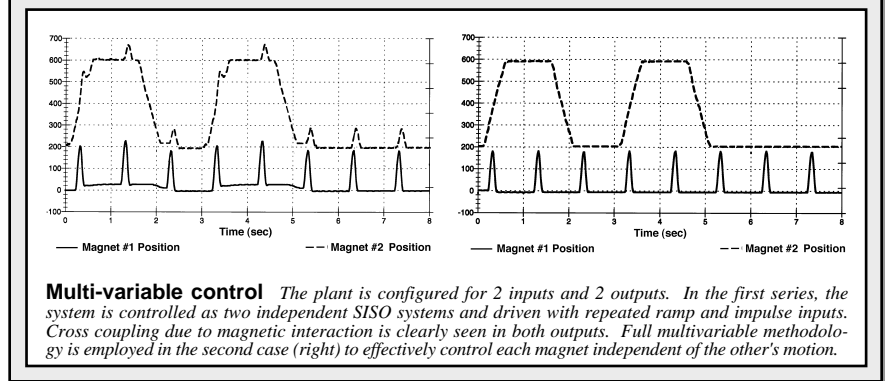
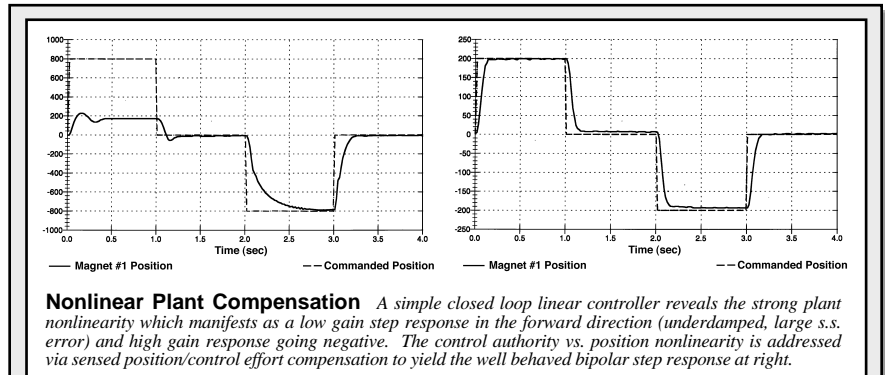


## Thought-provoking Experiments

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

Initial tests perform system identification to quantify the plant parameters and measure the strong nonlinearities. Early experiments demonstrate application of simple linear closed loop control to stabilize and regulate the closed loop system about some setpoint. It is shown that for the open loop stable plant, (see front page) the system is stabilizable for all positive gains but that for the unstable plant a minimum gain (bandwidth) is necessary for closed loop stability. Further tests vividly show the effect of the nonlinear dynamics on closed loop tracking control (see upper plots). By inverting these dynamics, rapid and precise tracking control is demonstrated.

MIMO experiments are included that demonstrate a range of design approaches including LQR, pole placement, and loop shaping methodologies. The system is tested (lower plots) with the two magnets controlled independently which produces much cross coupling in their motion. By implementing a full multivariable control law, effective and uncoupled control is accomplished. Other exciting experiments including disturbance rejection and induced field levitation using the optional turntable are provided.



## Turn-key Systems\* for Easy Setup & Operation



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

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

## Quality Components Provide High System Performance

Range of Motion	15 cm total. 6 cm indefinitely 10 cm momentarily ea. actuator
Magnets	Very high flux, rare earth NdFeB, with laser reflective coating
Sensors	Laser light amplitude with low noise, stray light rejection circuitry
Drive Coils	Low inductance, high field constant, air core
Drive Amplifiers	Linear range $\pm 40V$ out, 500 Hz current loop bandwidth
Size & Weight	36x36x30 cm. (14x14x12 in.), 5.1 kg. (11 lb.)
Turntable Accessory	Dynamically balanced spin platter, 0-500 RPM
Accessory Sensor & Actuator	Optical encoder, 12,000 counts/rev. Rare earth, servo motor
Accessory Size & Weight	38x38x15 cm. (15x15x6in.), 4.3 kg. (9.5 lb.)

## Contact us For More Information

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