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ANALOG AND LABVIEW-BASED CONTROL OF A MAGLEV SYSTEM WITH NI-ELVIS

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View from 5th floor of Olin Engineering Bldg, Oct 27, 2005

Outline of Presentation

- **Objectives**
- **Background**
- **Maglev Testbed**
- **Control Strategies**
- **Simulation Studies**
- **Experimental Studies**
- **Summary**
- **Future Work**

Objectives

Using a low cost maglev system for mechatronics education:

- Develop a linearized model
- Investigate classical linear controllers
- Implement controllers using analog circuits on NI-ELVIS
- “Implement” controllers using LabVIEW
- Compare performance of controllers

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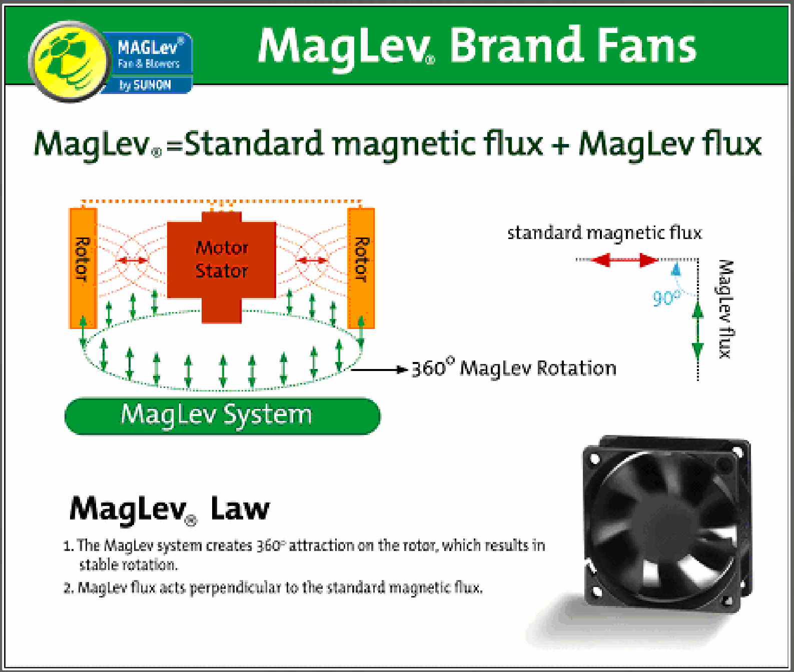
What is Maglev?

- **Maglev = Mag**netic **Lev**itation
- Levitate objects by electro-magnetic forces to cancel effect of gravity
- Established technology :
  - high-speed maglev vehicles
  - maglev bearings
  - vibration isolation systems, etc.

Examples


Maglev train
(China)
(speeds of 430 km/h)


Maglev Bearing


MAGLev
Fan & Blowers
by SUNON
MagLev Brand Fans
MagLev =Standard magnetic flux + MagLev flux
Rotor
Motor
Stator
Rotor
standard magnetic flux
90°
MagLev flux
360° MagLev Rotation
MagLev System
MagLev Law
1. The MagLev system creates 360° attraction on the rotor, which results in stable rotation.
2. MagLev flux acts perpendicular to the standard magnetic flux.


Levitron

Control Strategies

- **Linear Control**
  - Classical PID
  - PID with gain scheduling
  - Phase-lead, Phase-lag
  - LQR, LQE, LQG, H_∞, μ-synthesis
- **Nonlinear Control**
  - On-off
  - PWM
  - Fuzzy-logic
  - Neural-network control
  - Feedback linearization
  - Adaptive control
  - Backstepping theory

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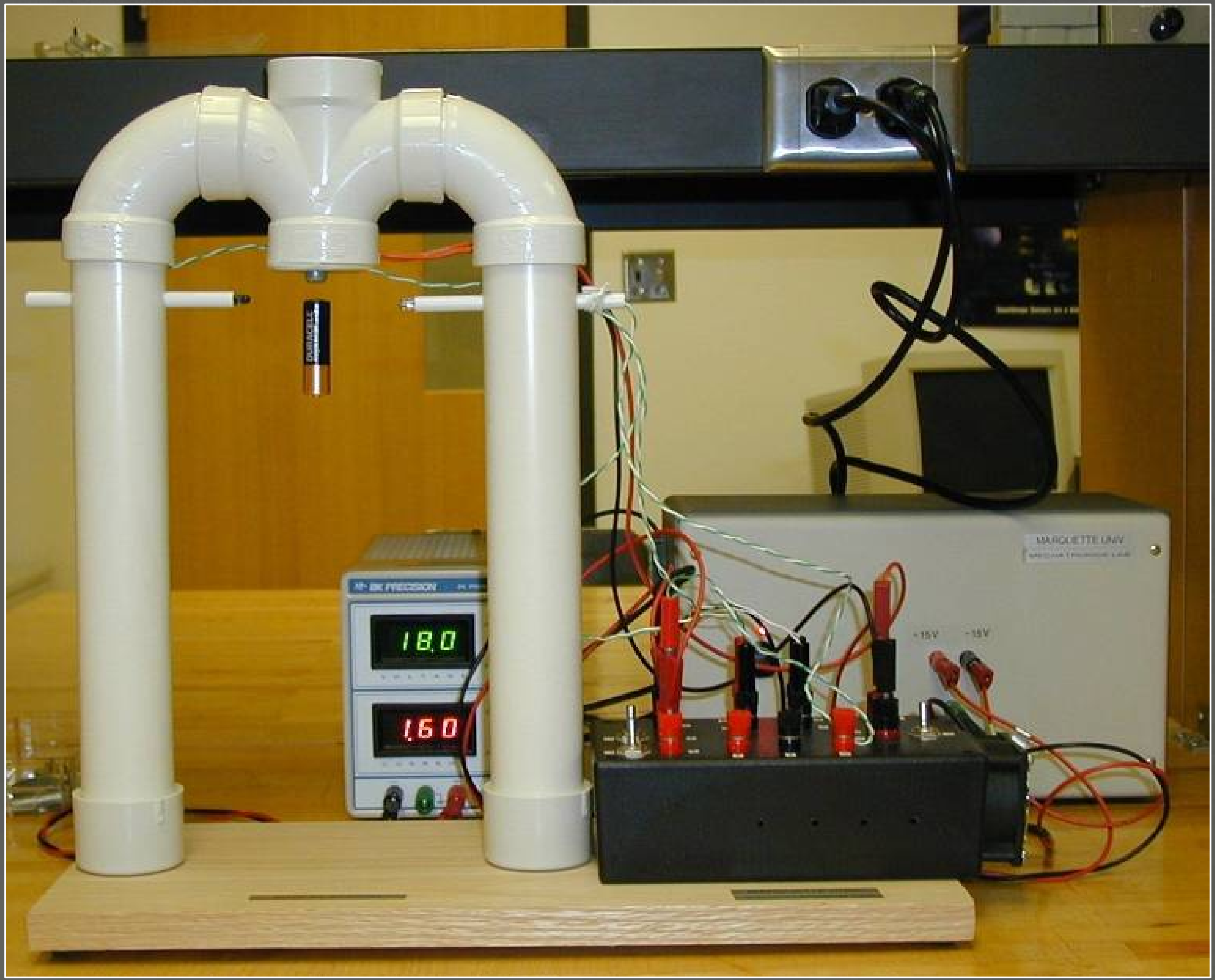
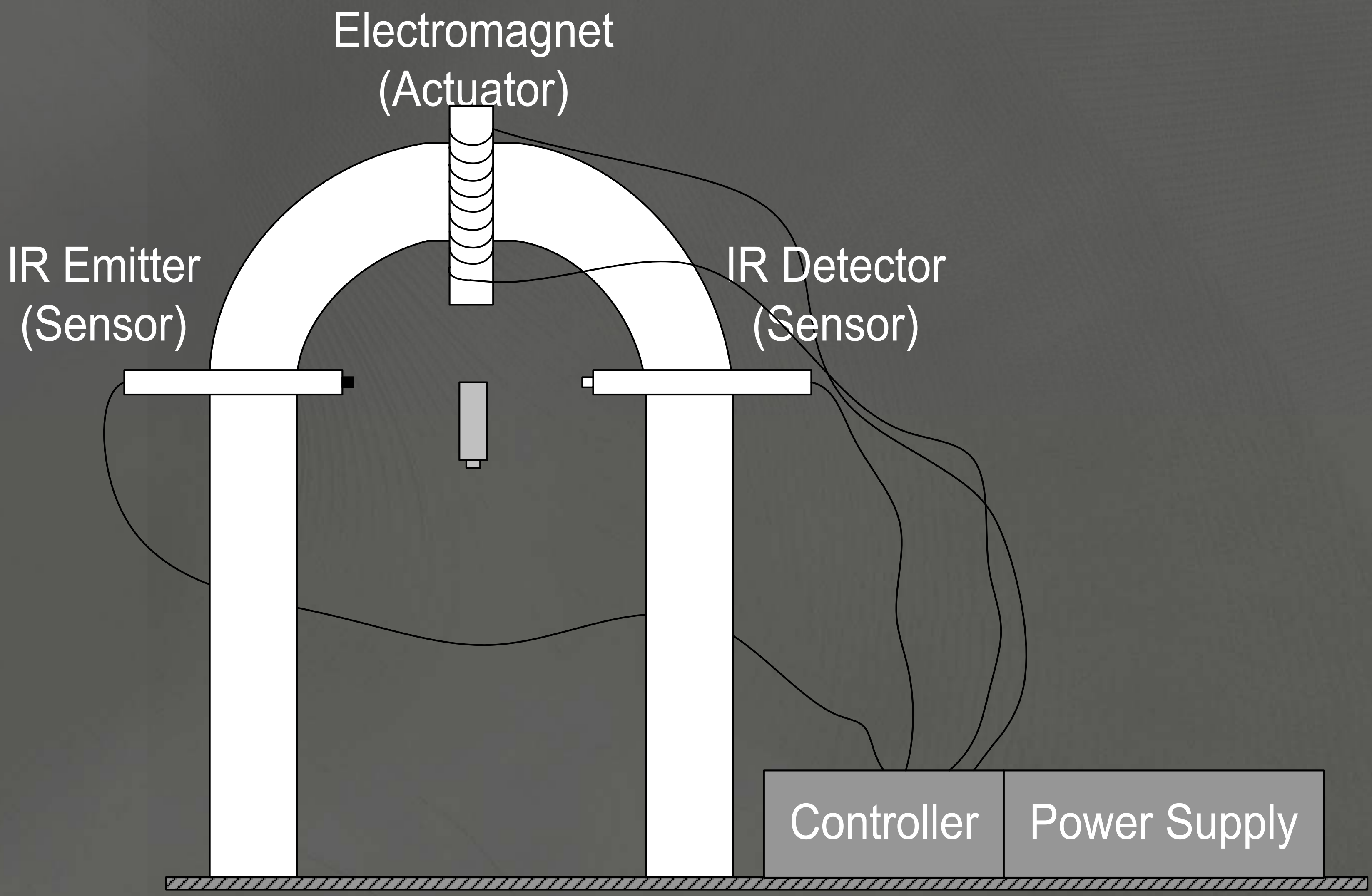
Physical Testbed

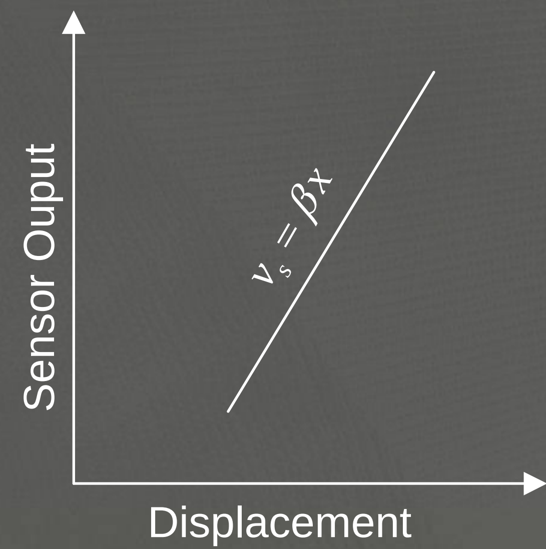


Testbed Pictorial



Infrared (IR) Sensor

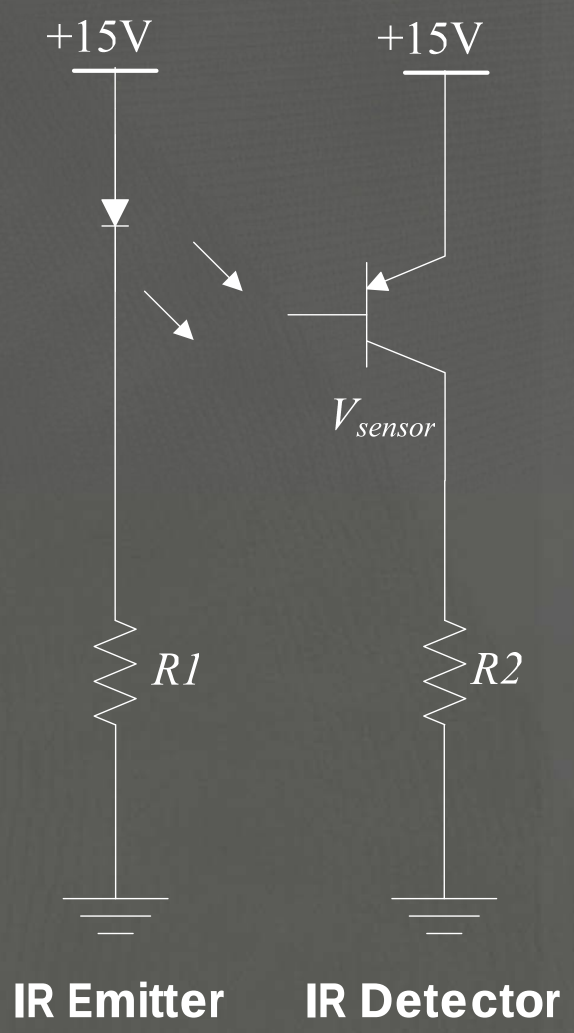
- Infrared emitter and detector pair
- Acts as a variable resistor
- Levitated object blocks path, changes light intensity
- Linear behavior in operating region



$$v_s = \beta x$$

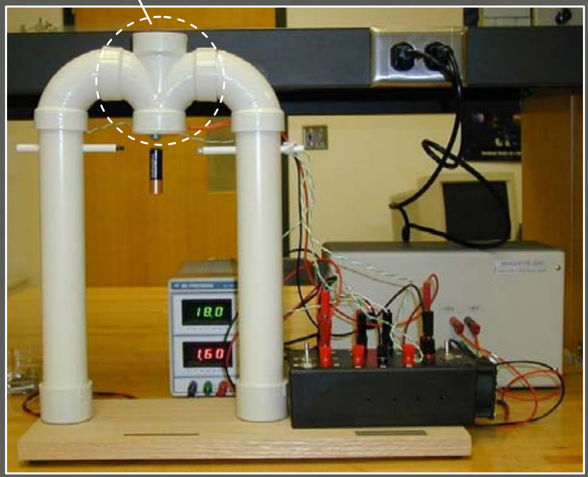
Sensor and Controls Logic

- The emitter generates constant light intensity.
- The detector signal is amplified and compared with a reference voltage.
- Difference of signals used to adjust current to electromagnet.
  - If the levitated object is too close to electromagnet (detected IR signal too small), the current is reduced.
  - If the levitated object is too far (detected IR signal too large), the current is increased.



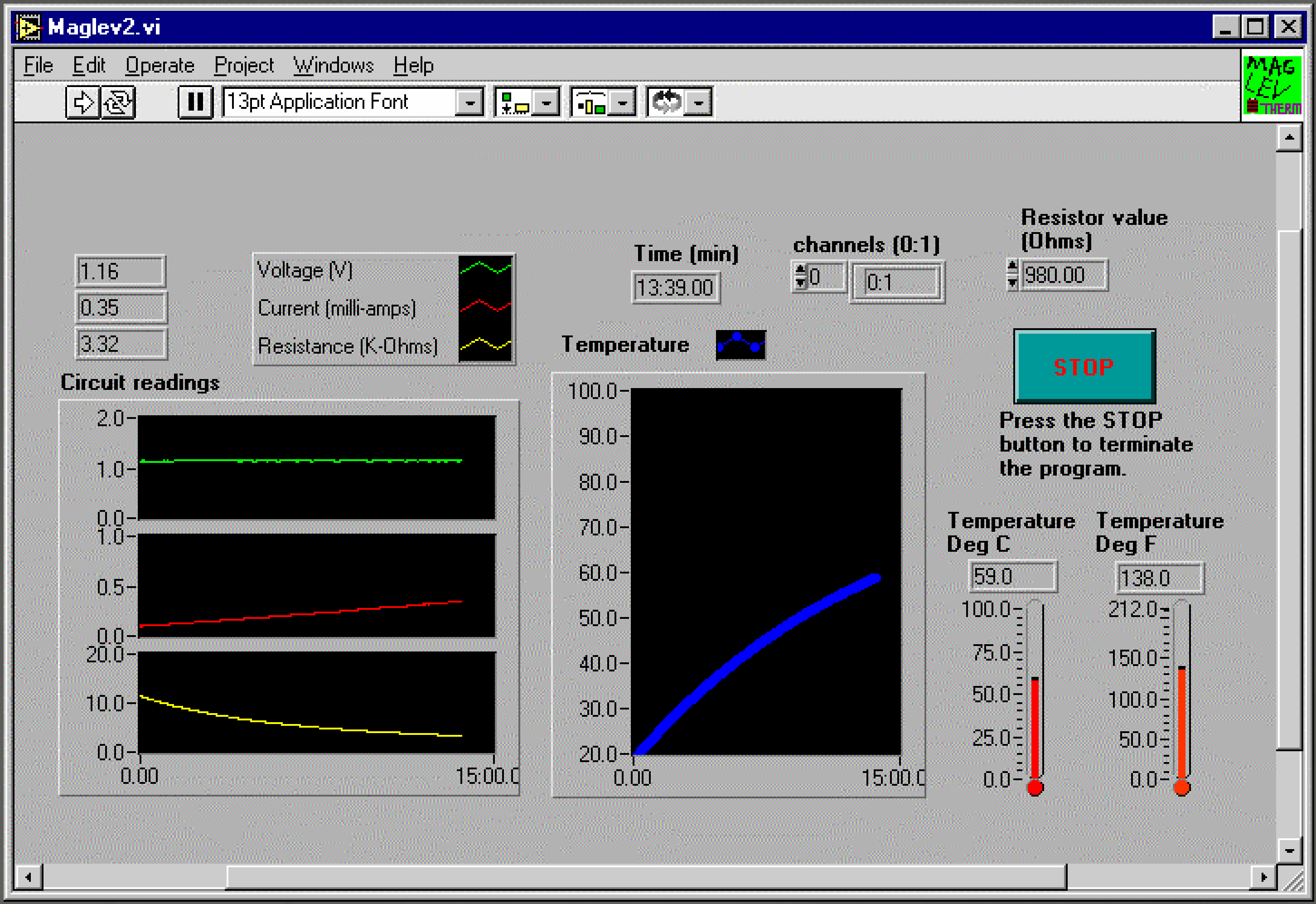
Actuator

- Actuator is electro-magnetic coil with steel bolt core
- Electromagnet obtained commercially
- FEA performed to check for magnetic saturation
- Power supply: 18 V / 3 A



Maglev Temperature Expt.

Thermistor mounted to coil used to measure temperature during levitation



Nonlinear Model

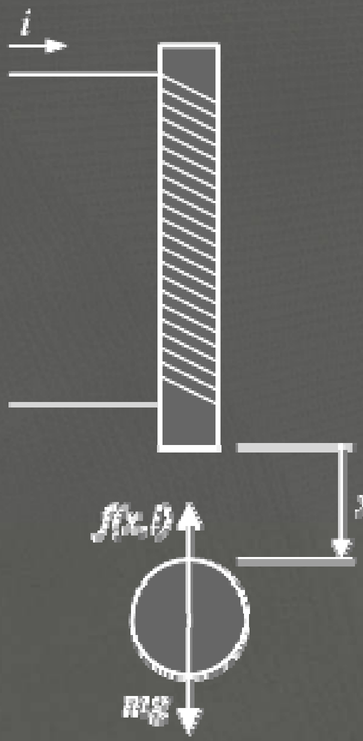
$$f\left(x,i,t\right) = -\frac{i\left(t\right)^2}{2}\frac{dL\left(x\right)}{dx}$$

$$L\left(x\right) = L_1 + \frac{L_o x_o}{x}$$

$$f\left(x,i,t\right) = \frac{L_o x_o}{2}\left(\frac{i\left(t\right)}{x\left(t\right)}\right)^2 = C\left(\frac{i\left(t\right)}{x\left(t\right)}\right)^2$$

$$m\frac{d^2x\left(t\right)}{dt^2} = mg - f\left(x,i,t\right)$$

$$\boxed{m\frac{d^2x\left(t\right)}{dt^2} = mg - C\left(\frac{i\left(t\right)}{x\left(t\right)}\right)^2}$$



Linearized Model

$$f\left(x,i,t\right)=C\left(\frac{i_o}{x_o}\right)^2+\left(\frac{2Ci_o}{x_o^2}\right)i\left(t\right)-\left(\frac{2Ci_o^2}{x_o^3}\right)x\left(t\right)+\ldots$$

$$f\left(x,i,t\right)=f_o+f_1+\ldots$$

$$f_o\left(x,i\right)=C\left(\frac{i_o}{x_o}\right)^2=mg$$

$$f_1\left(x,i,t\right)=\left(\frac{2Ci_o}{x_o^2}\right)i\left(t\right)-\left(\frac{2Ci_o^2}{x_o^3}\right)x\left(t\right)$$

$$m\frac{d^2x\left(t\right)}{dt^2}=mg-f$$

$$m\frac{d^2x\left(t\right)}{dt^2}=mg-f_o-\left(\frac{2Ci_o}{x_o^2}\right)i\left(t\right)+\left(\frac{2Ci_o^2}{x_o^3}\right)x\left(t\right)$$

Linearized Model (cont'd)

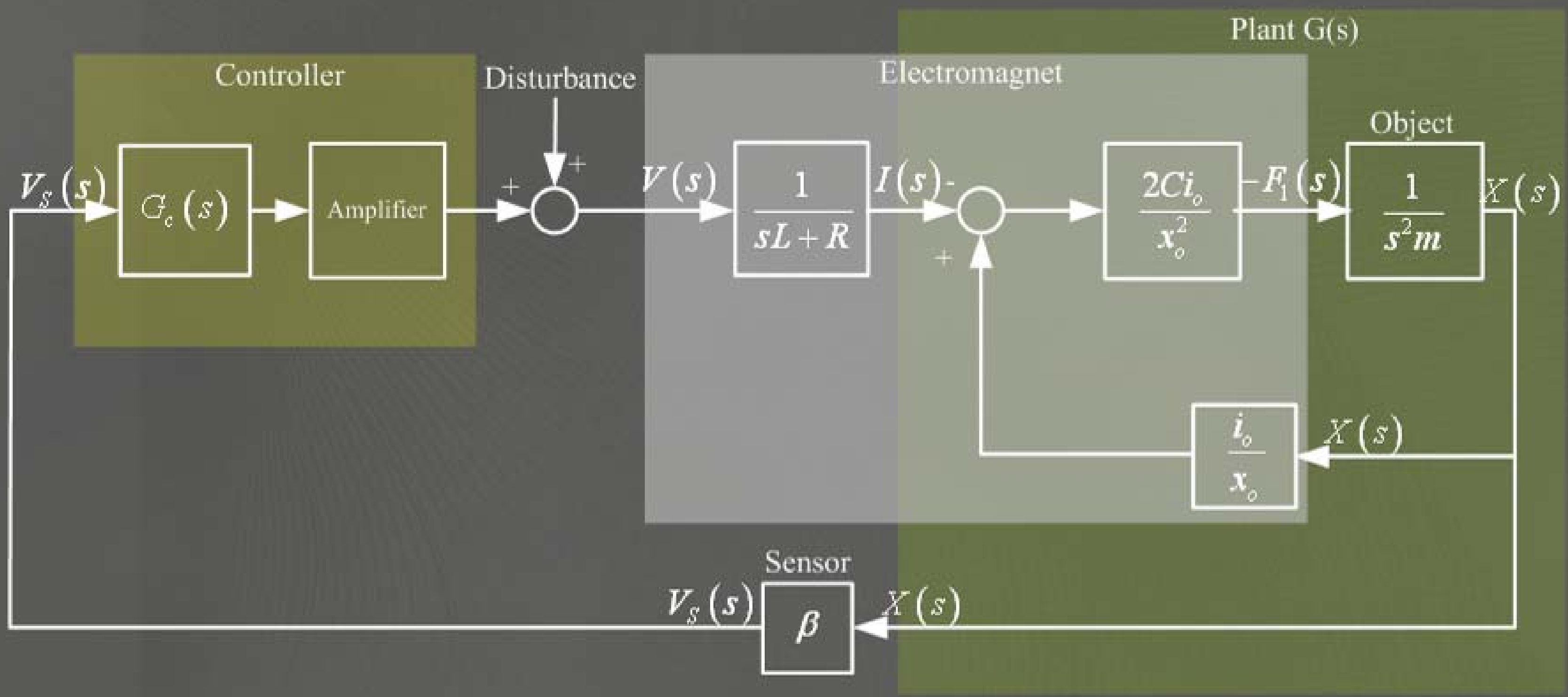
$$f_o = C\left(\frac{i_o}{x_o}\right)^2 = mg$$

$$m\frac{d^2x(t)}{dt^2} = -\left(\frac{2Ci_o}{x_o^2}\right)i(t) + \left(\frac{2Ci_o^2}{x_o^3}\right)x(t)$$

$$ms^2X(s) = -\left(\frac{2Ci_o}{x_o^2}\right)I(s) + \left(\frac{2Ci_o^2}{x_o^3}\right)X(s)$$

$$G(s) = \frac{X(s)}{I(s)} = \frac{-\left(\frac{2Ci_o}{x_o^2}\right)}{ms^2 - \left(\frac{2Ci_o^2}{x_o^3}\right)} = \frac{-\left(\frac{2Ci_o}{mx_o^2}\right)}{s^2 - \left(\frac{2Ci_o^2}{mx_o^3}\right)}$$

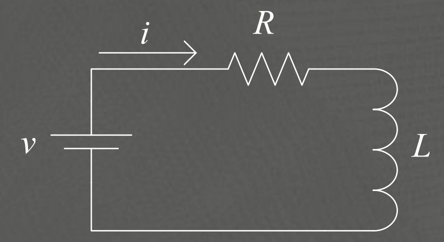
Block Diagram



$$G(s)=\frac{X(s)}{I(s)}=\frac{-\left(\frac{2Ci_o}{x_o^2}\right)}{s^2 m-\left(\frac{2Ci_o^2}{x_o^3}\right)}=\frac{-\left(\frac{2Ci_o}{mx_o^2}\right)}{s^2-\left(\frac{2Ci_o^2}{mx_o^3}\right)}$$

Alternate Plant Transfer Function

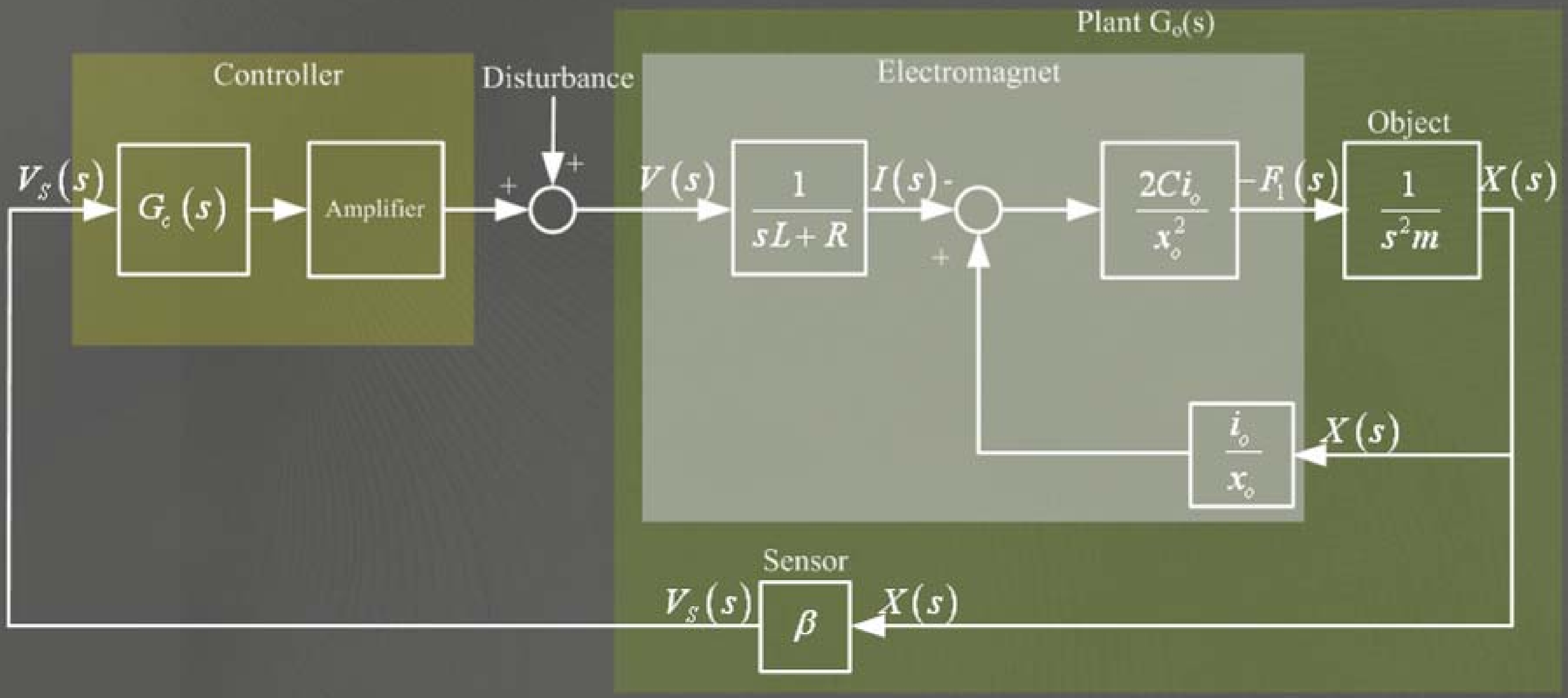
- The electromagnet represented as a series combination of a resistor and inductor
- Consider sensor output as the system output
- Consider voltage to the electromagnet as the system input



$$v(x,i,t) = Ri(t) + L(x)\frac{di(t)}{dt}$$

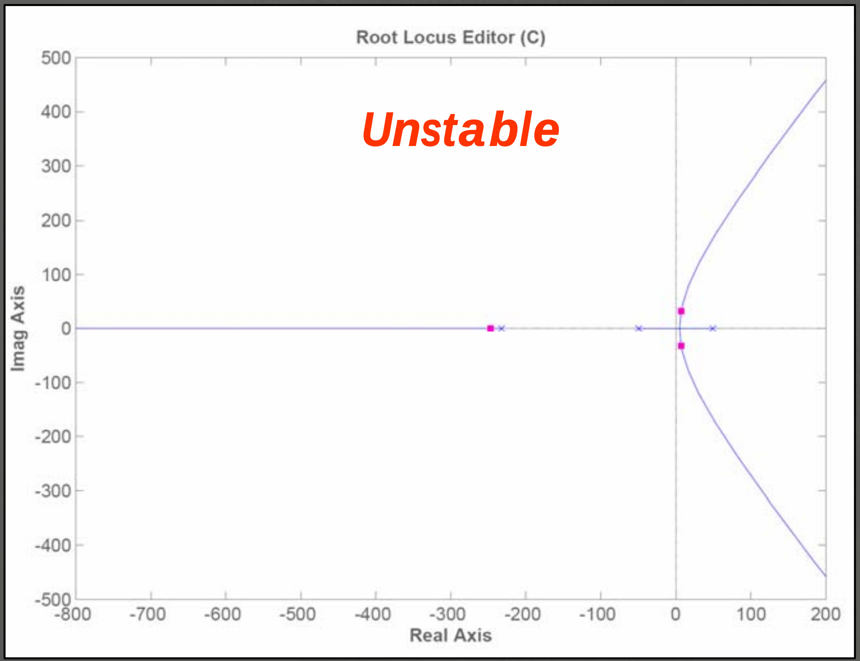
$$G_o(s) = \frac{V_s(s)}{V(s)} = \frac{\left(\dfrac{-2\beta C i_o}{mLx_o^2}\right)}{\left(s + \dfrac{R}{L}\right)\left(s^2 - \dfrac{2Ci_o^2}{mx_o^3}\right)}$$

Block Diagram II

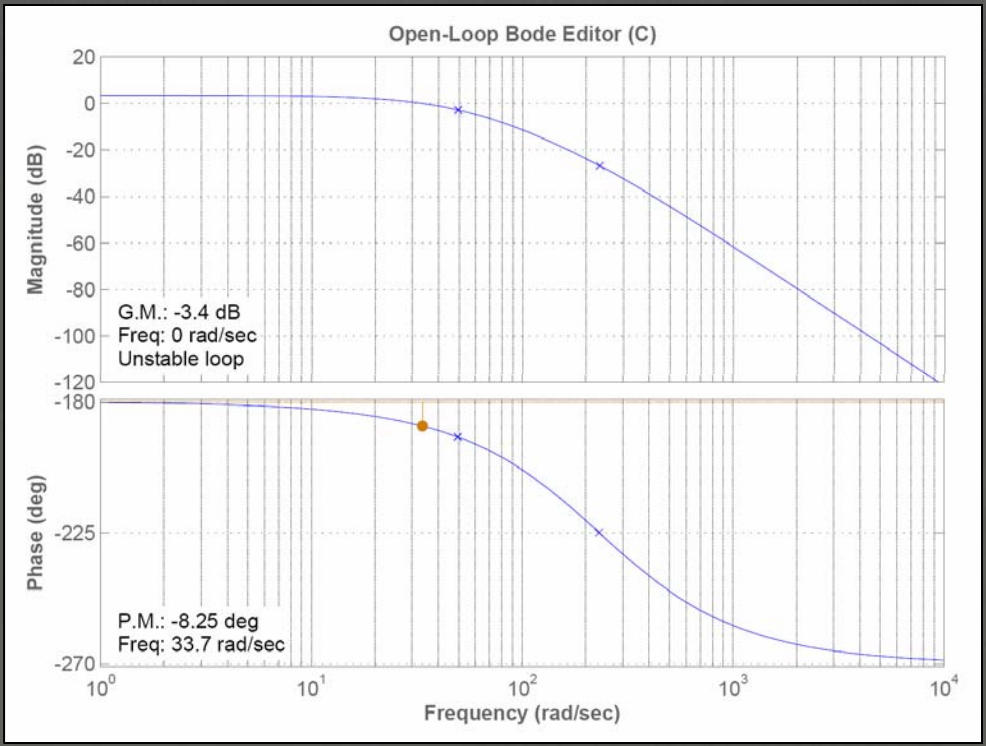


$$G_o(s) = \frac{V_s(s)}{V(s)} = \frac{\left(\dfrac{-2\beta C i_o}{mLx_o^2}\right)}{\left(s + \dfrac{R}{L}\right)\left(s^2 - \dfrac{2Ci_o^2}{mx_o^3}\right)}$$

Open-loop Analysis



$$G_o(s) = \frac{824000}{(s+232)(s+49.5)(s-49.5)}$$



The root-locus has a pole in the right-half plane; the system is **unstable**

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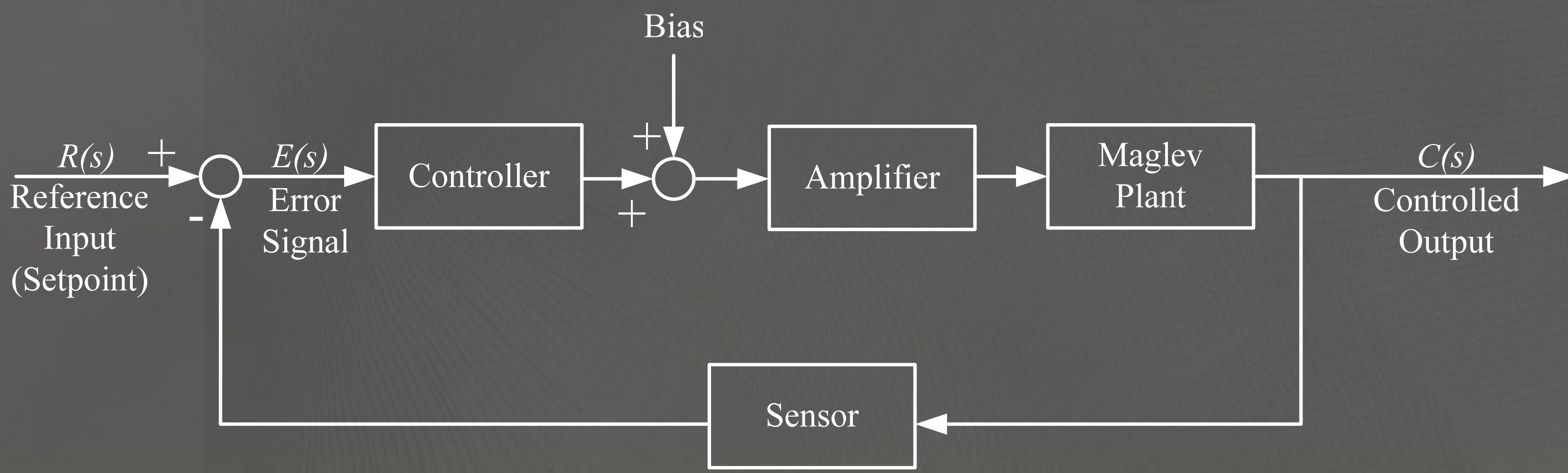
Control Block Diagram



- Error signal calculated as difference of setpoint and sensor output
- Error signal is input to controller
- Bias is added to controller output, amplified, and input to "maglev plant"
- Controlled output is actual output

$G_P(s) = K_P$ $G_{Lead}(s) = K\frac{s+z}{s+p} \simeq K(s+z) \quad (p \to \infty)$

Control Strategies

- **Proportional Control**
  - Controller output is proportional to error

$$G_P(s) = K_P$$

- **Lead-Lag Control**
  - Adds a zero and a pole to the open-loop system

$$G_{Lead/Lag}(s) = K\frac{s+z}{s+p} \qquad \begin{array}{ll} Lead & for\ 0 < z < p \\ Lag & for\ 0 < p < z \end{array}$$

Control Strategies

- **PD Control**
  - Adds derivative term

$$G_{PD}(s) = K_P + K_D s$$

- **PID Control**
  - Integral term makes steady-state error zero

$$G_{PID}(s) = K_P + K_D s + \frac{K_I}{s}$$

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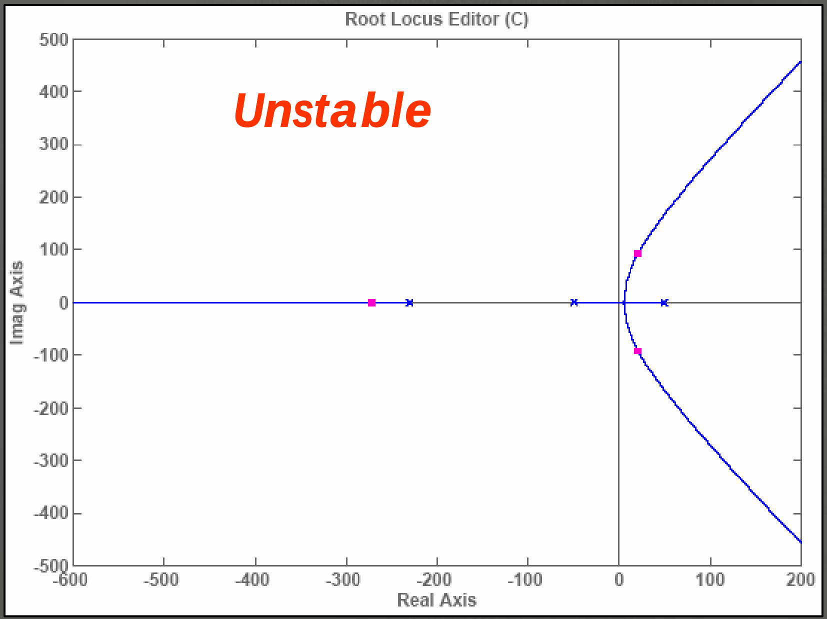
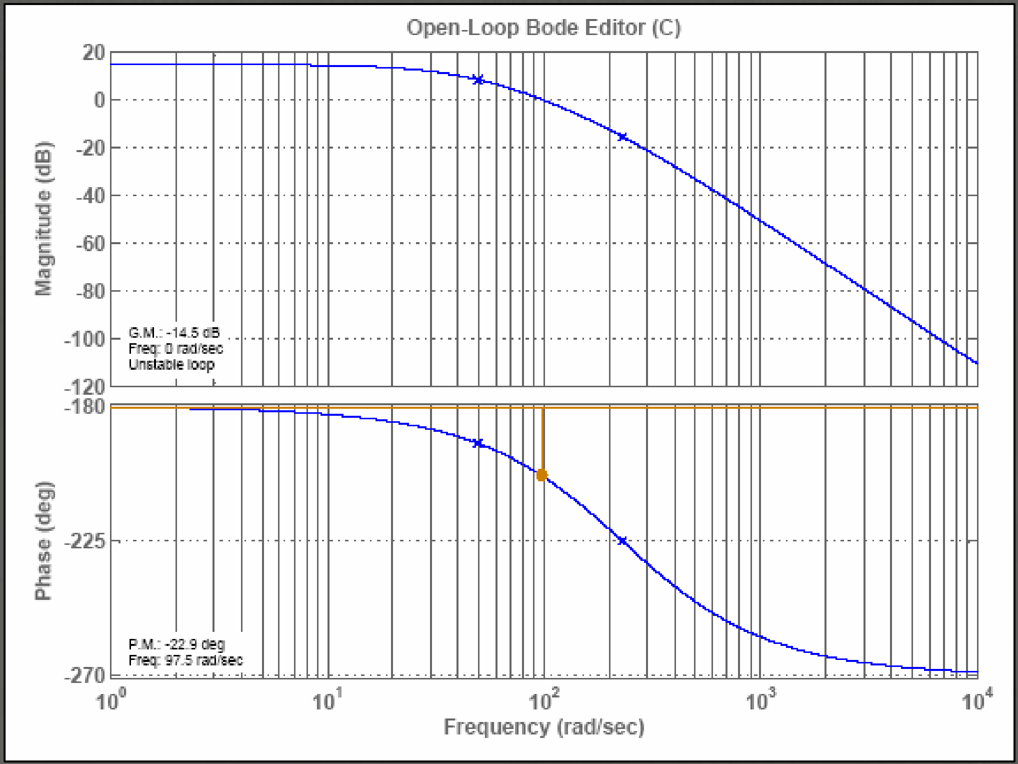
Proportional Controller

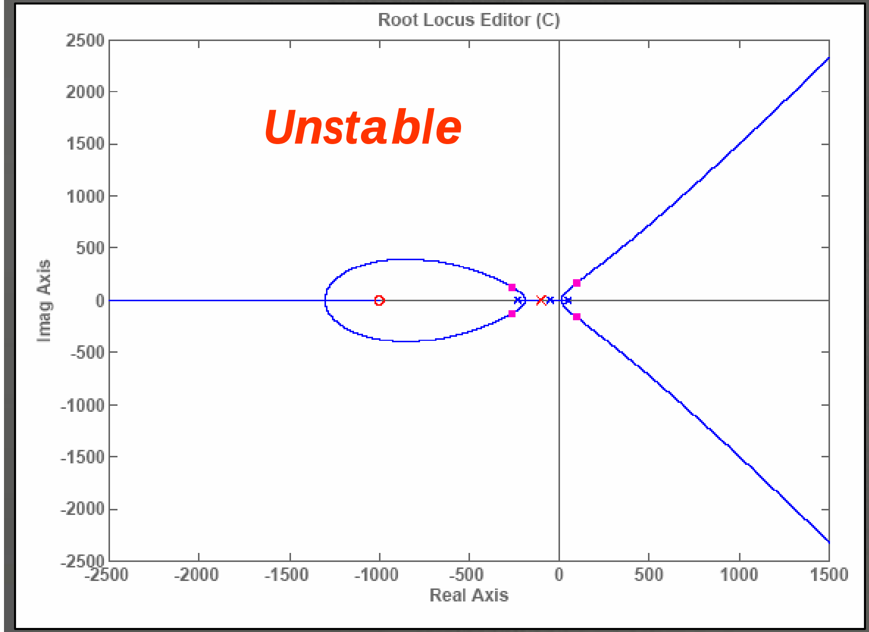


Proportional Controller acts as a gain; cannot move poles into left-half plane

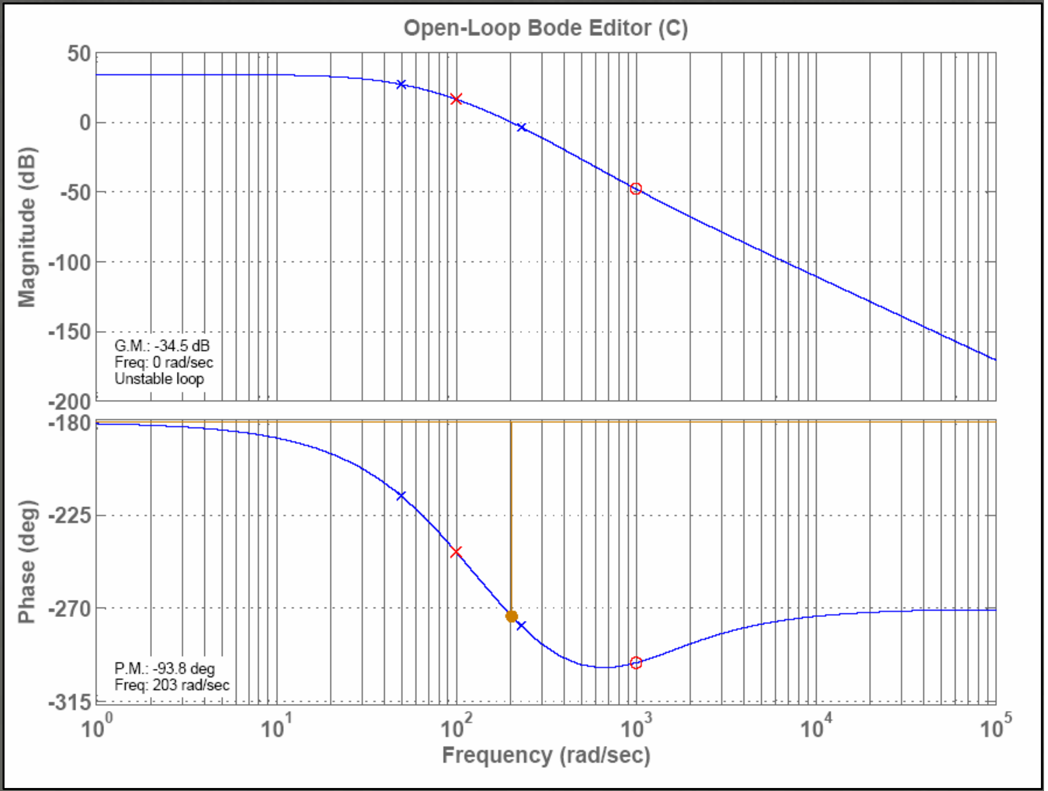
Proportional Controller by itself cannot stabilize open-loop unstable system



Lag Compensator

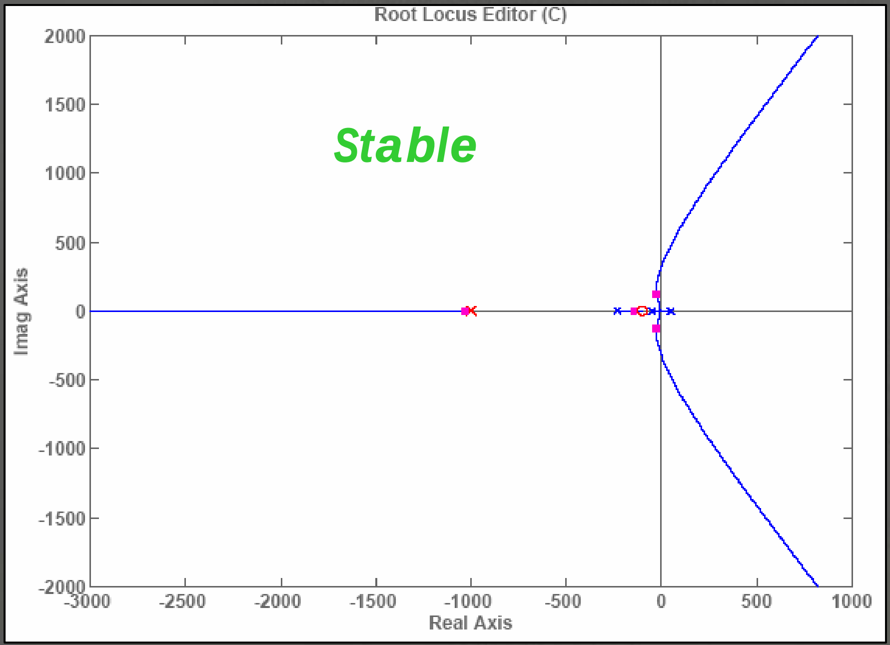


Lag Compensator cannot move poles into left-half plane

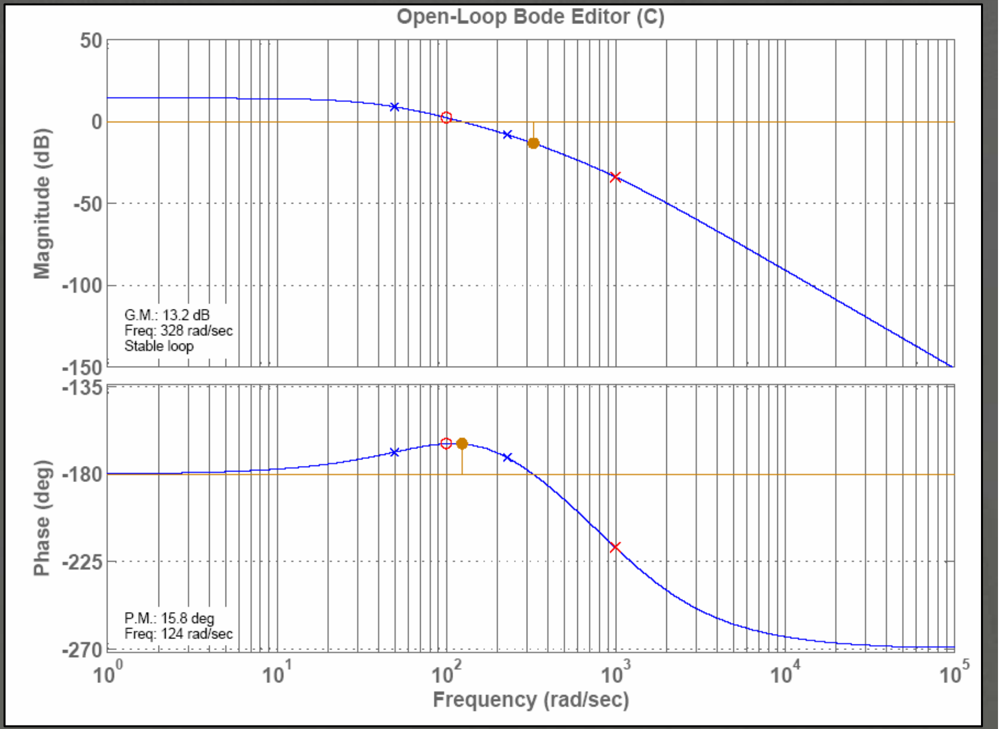


Lag Compensator by itself cannot stabilize an open-loop unstable system

Lead Compensator



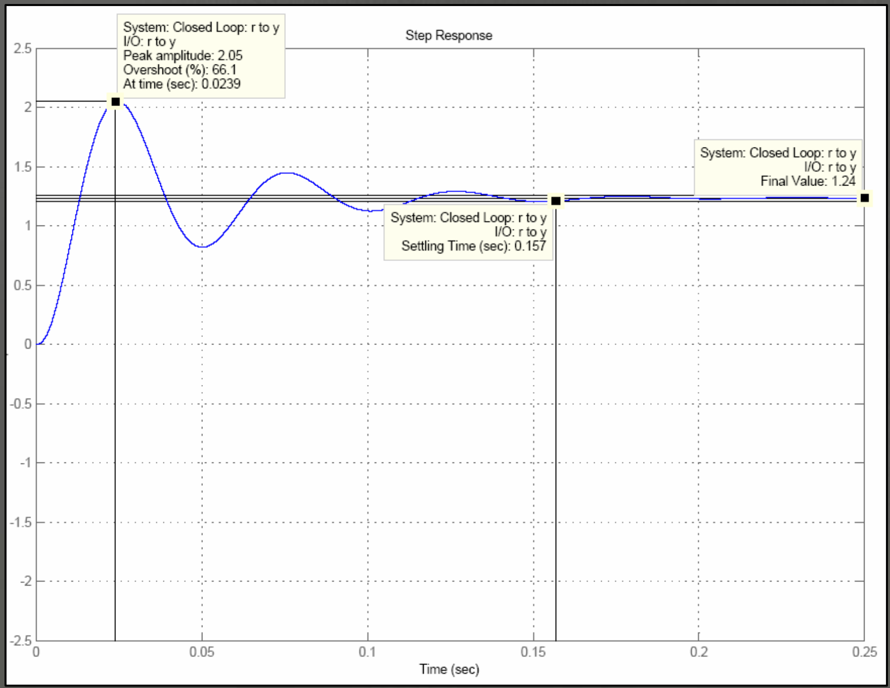
Lead Compensator moves poles into left-half plane



Lead Compensator can stabilize open-loop unstable system

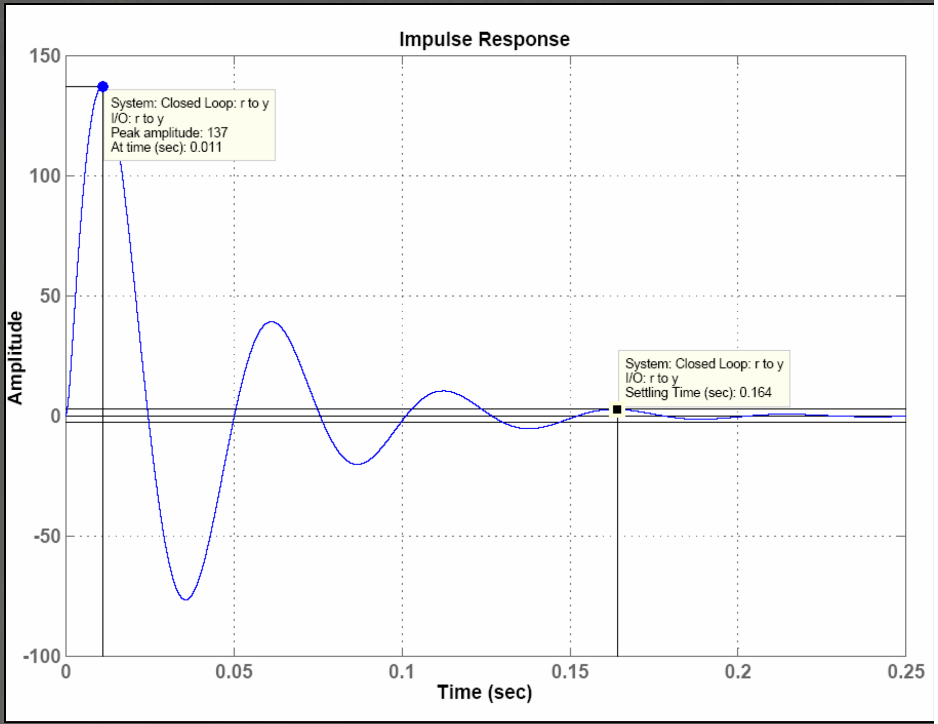
Gain Margin: 13.2 dB
Phase Margin: 15.8 deg

Lead Compensator Response



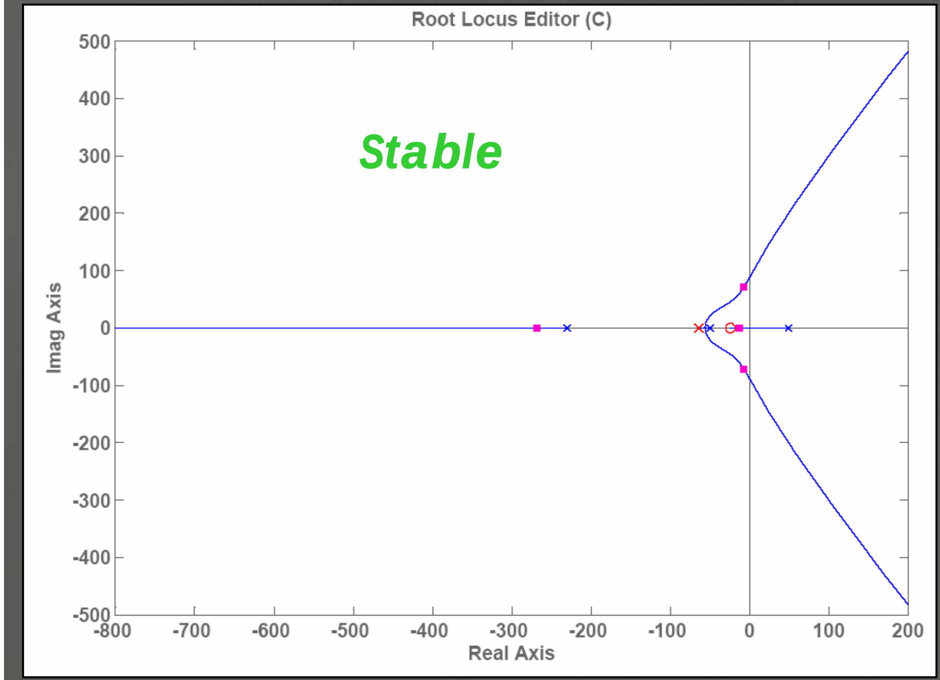
Step Response
Settling Time: 0.157s
Steady-State Error: 0.24

(Zero at -100 rad/s, Pole at -1000 rad/s)

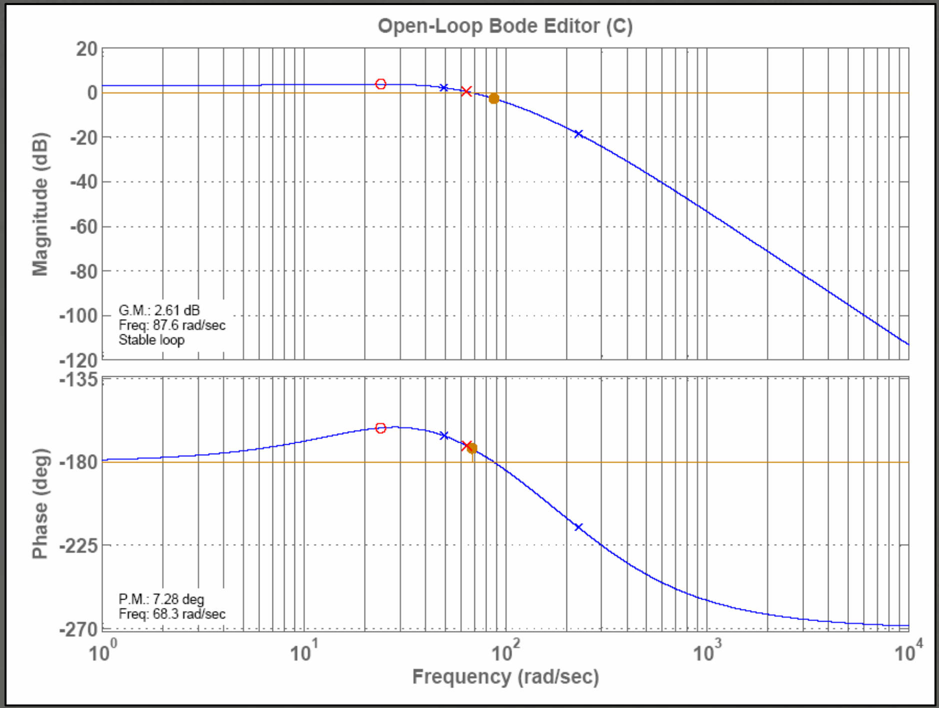


Impulse Response
Settling Time: 0.164s

PD Controller



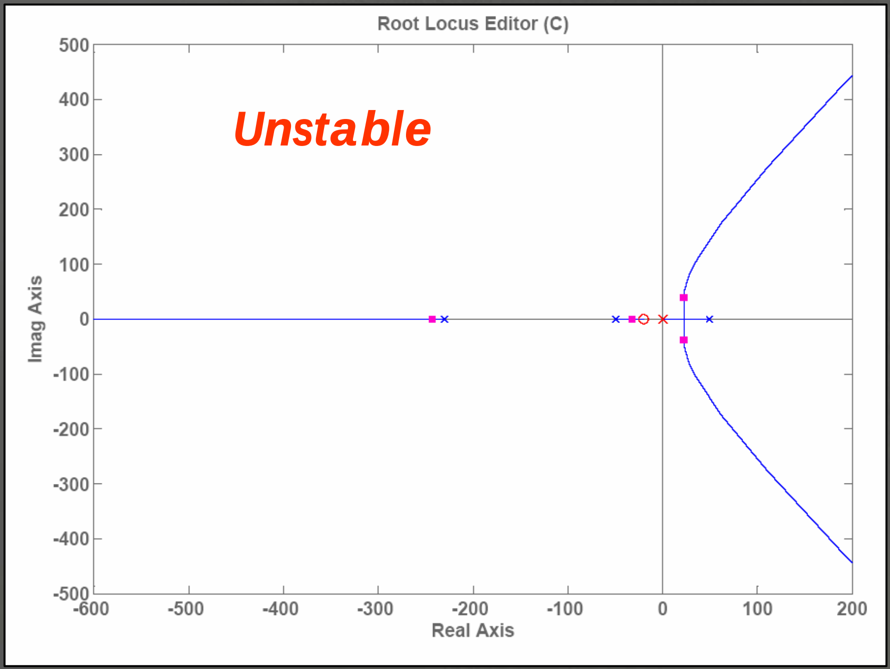
PD Controller moves poles into left-half plane



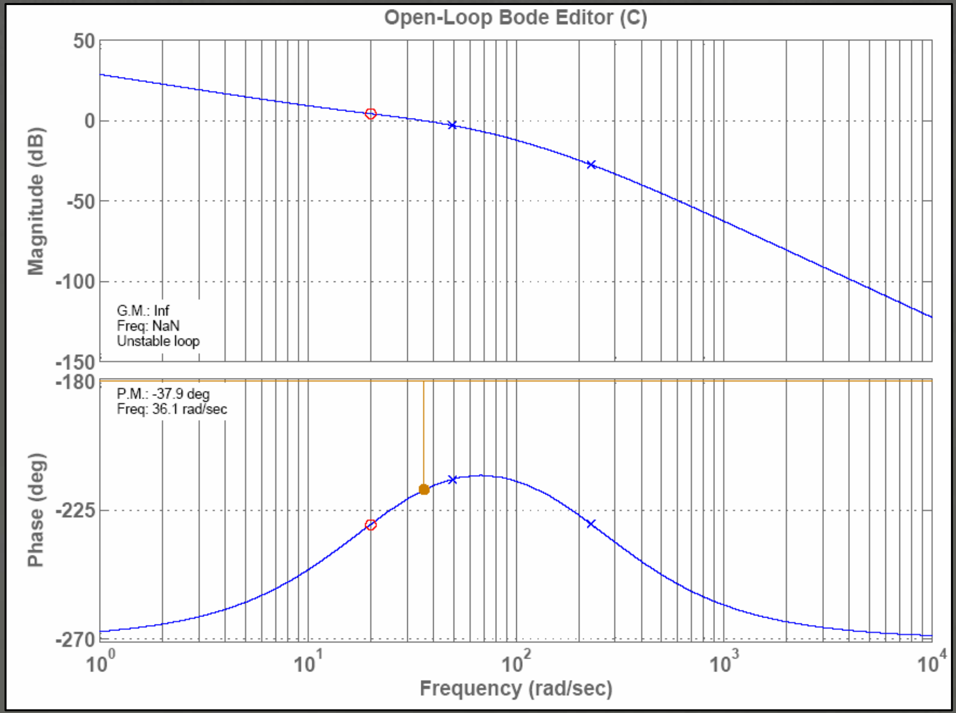
PD Controller can stabilize open-loop unstable system

Gain Margin: 2.61 dB
Phase Margin: 7.28 deg

PI Controller

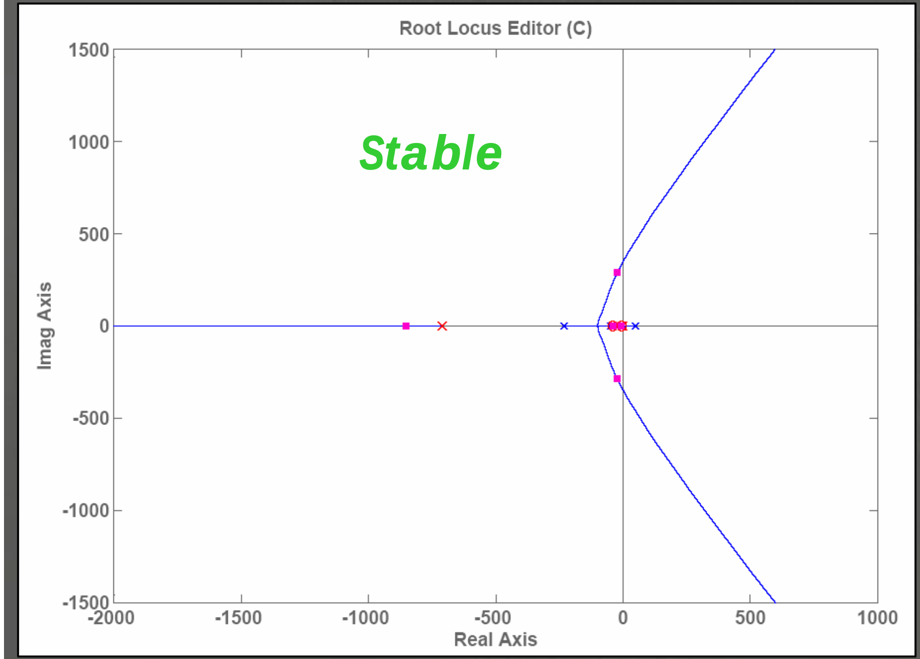


PI Controller cannot move poles into left-half plane

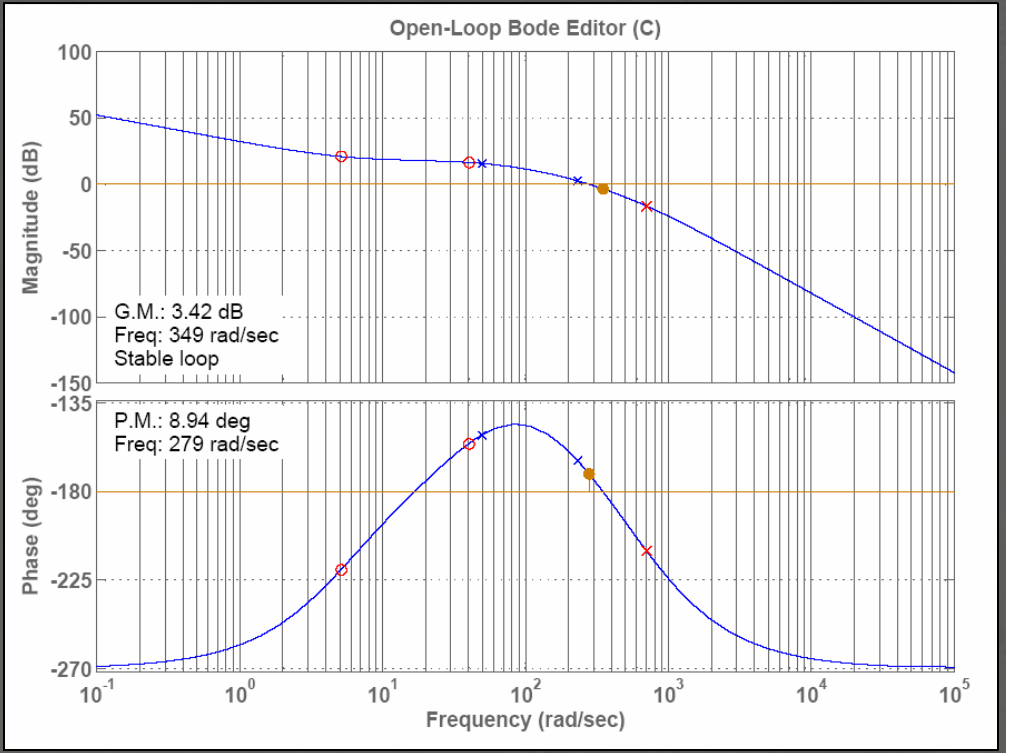


PI Controller cannot stabilize open-loop unstable system

PID Controller



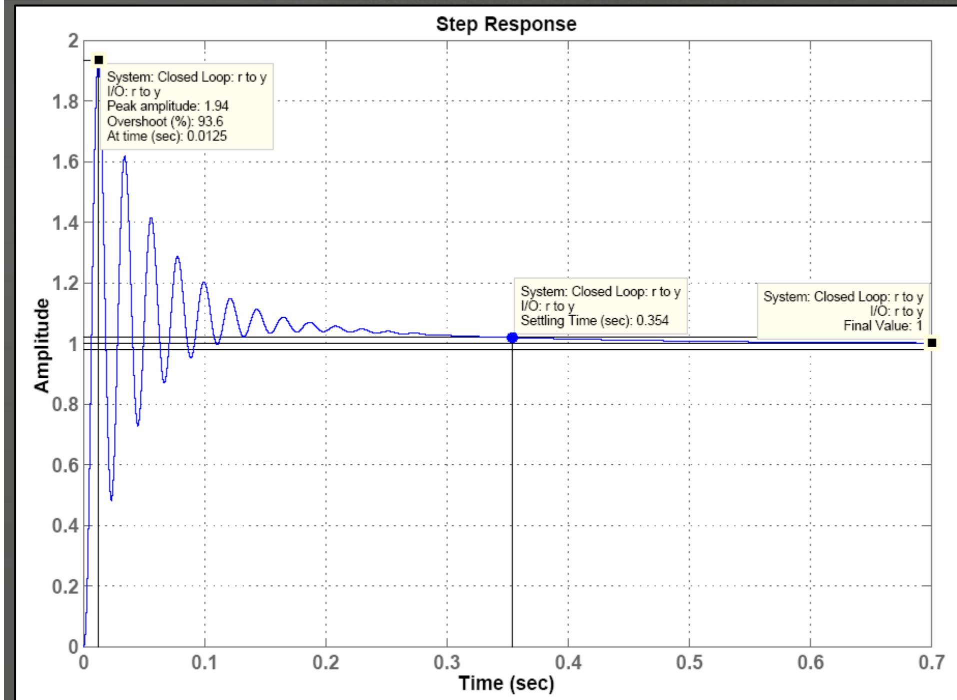
PID Controller moves poles into left-half plane



PID Controller can stabilize open-loop unstable system

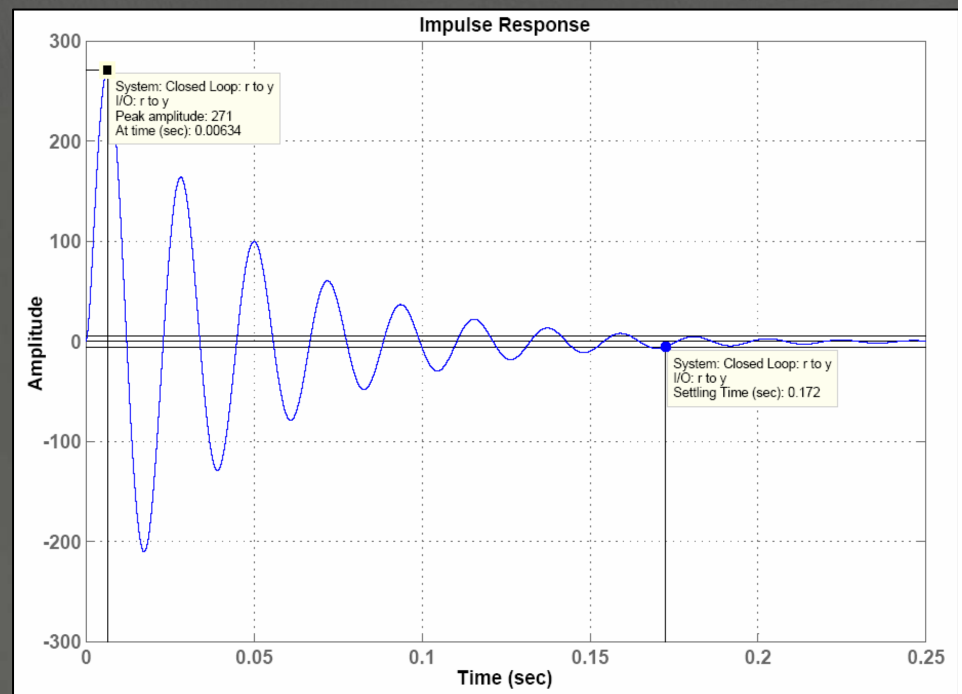
Gain Margin: 3.42 dB
Phase Margin: 8.94 deg

PID Controller Response



Step Response
Settling Time: 0.354s
Steady-State Error: 0

(K_P=0.68, K_I=3.12, K_D=0.0141)



Impulse Response
Settling Time: 0.172s

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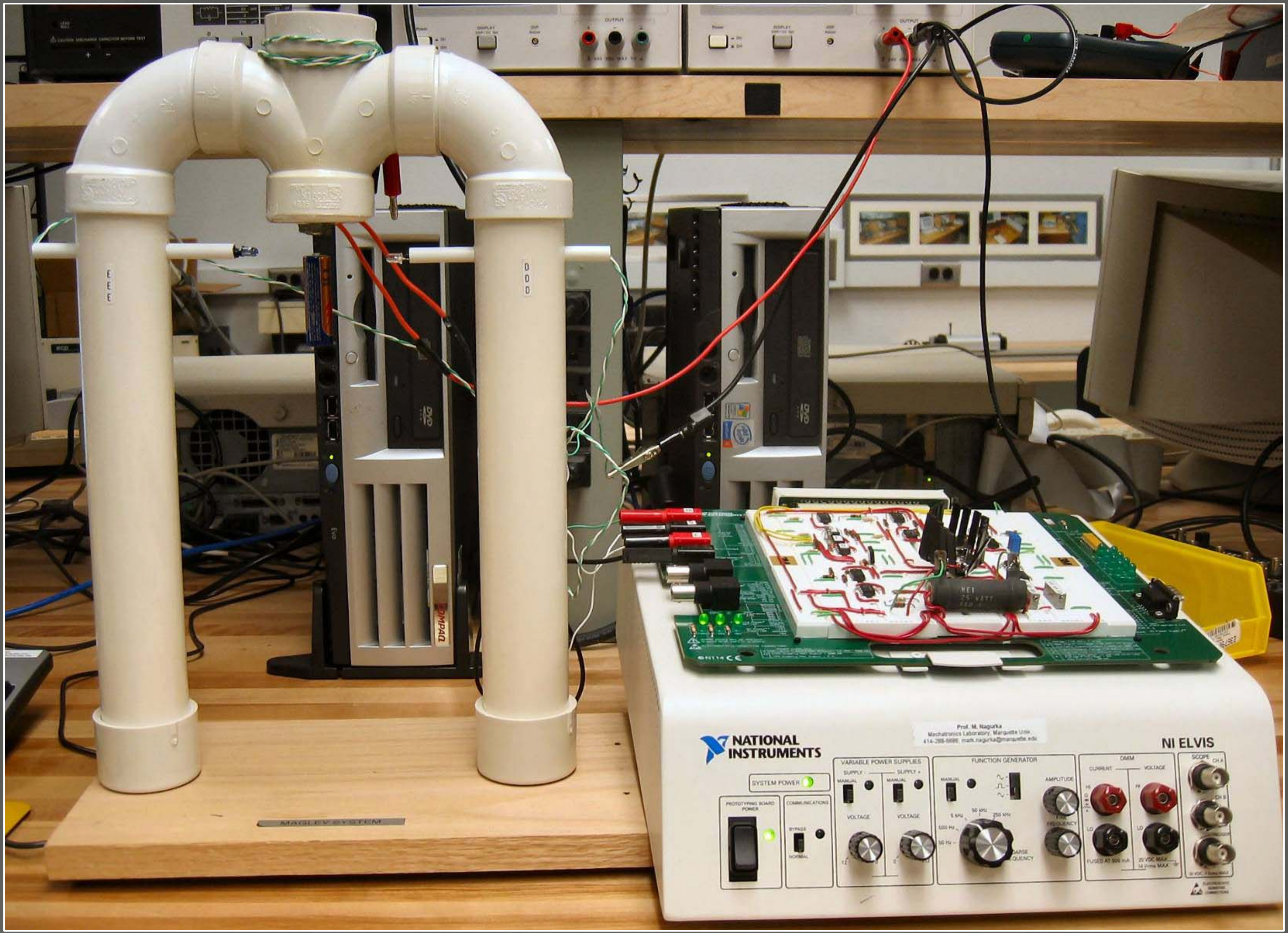
Maglev Experimental Station

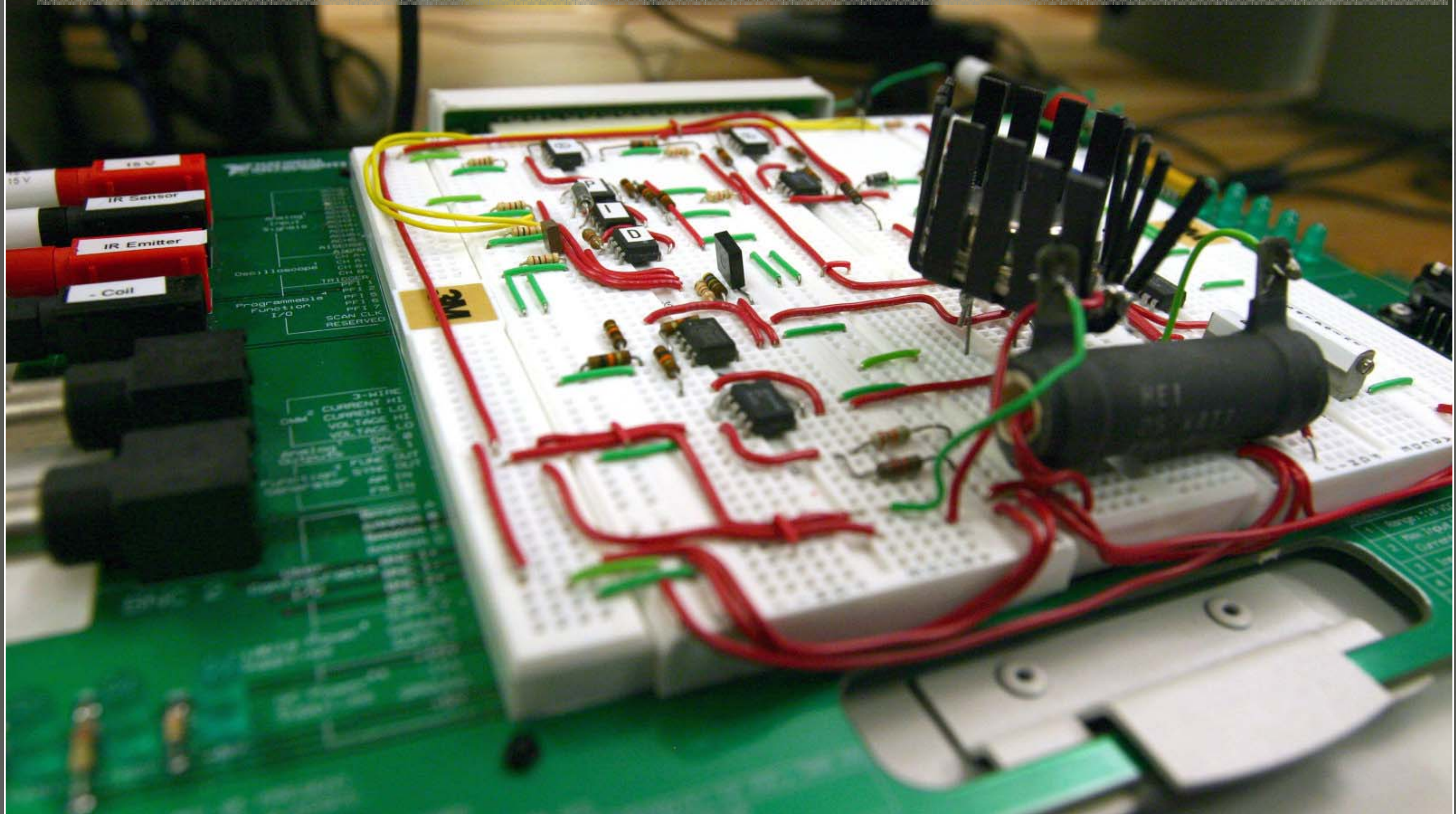


NI-ELVIS

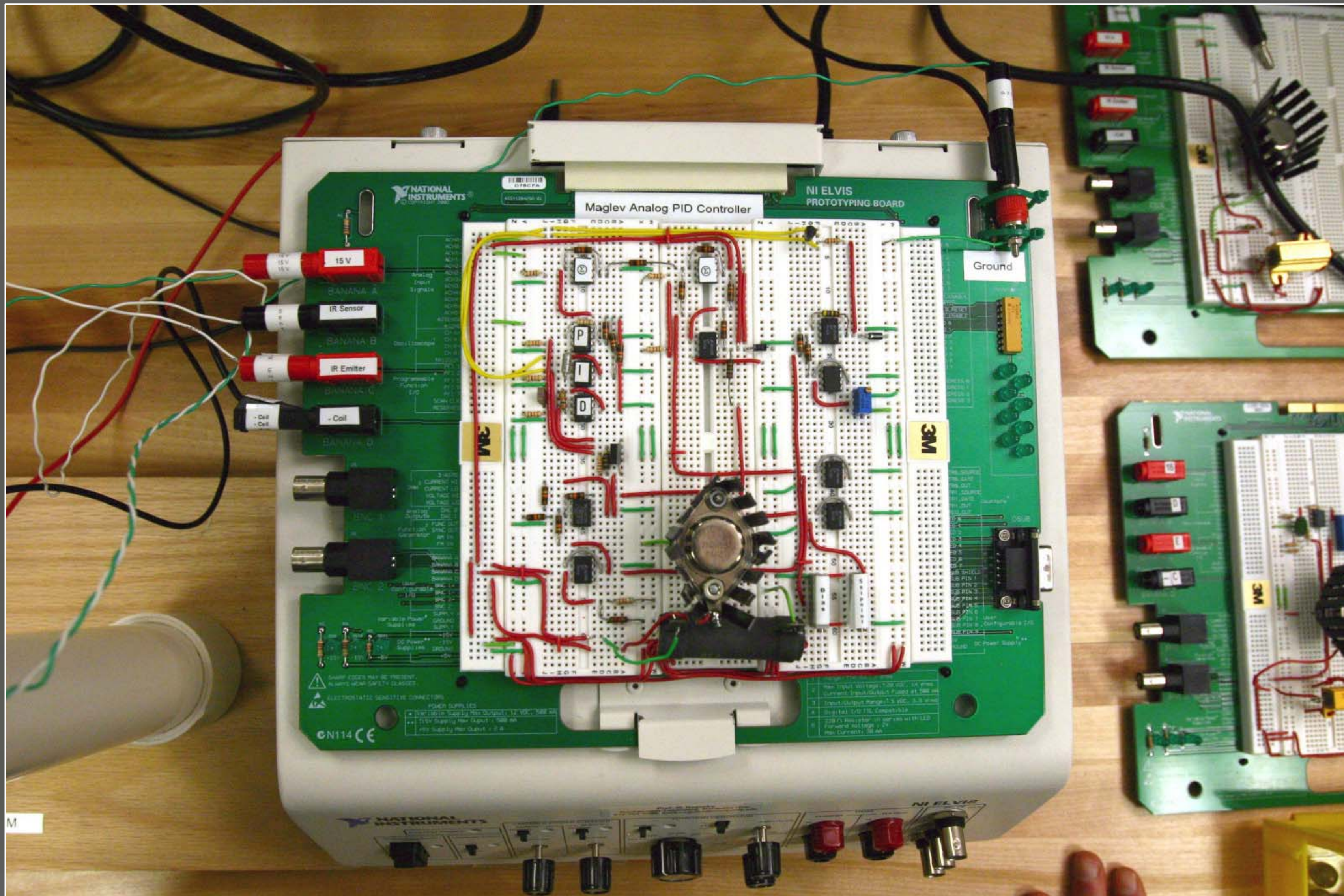
National **I**nstruments'
Educational **L**aboratory **V**irtual **I**nstrumentation **S**uite

NI-ELVIS Prototyping Board

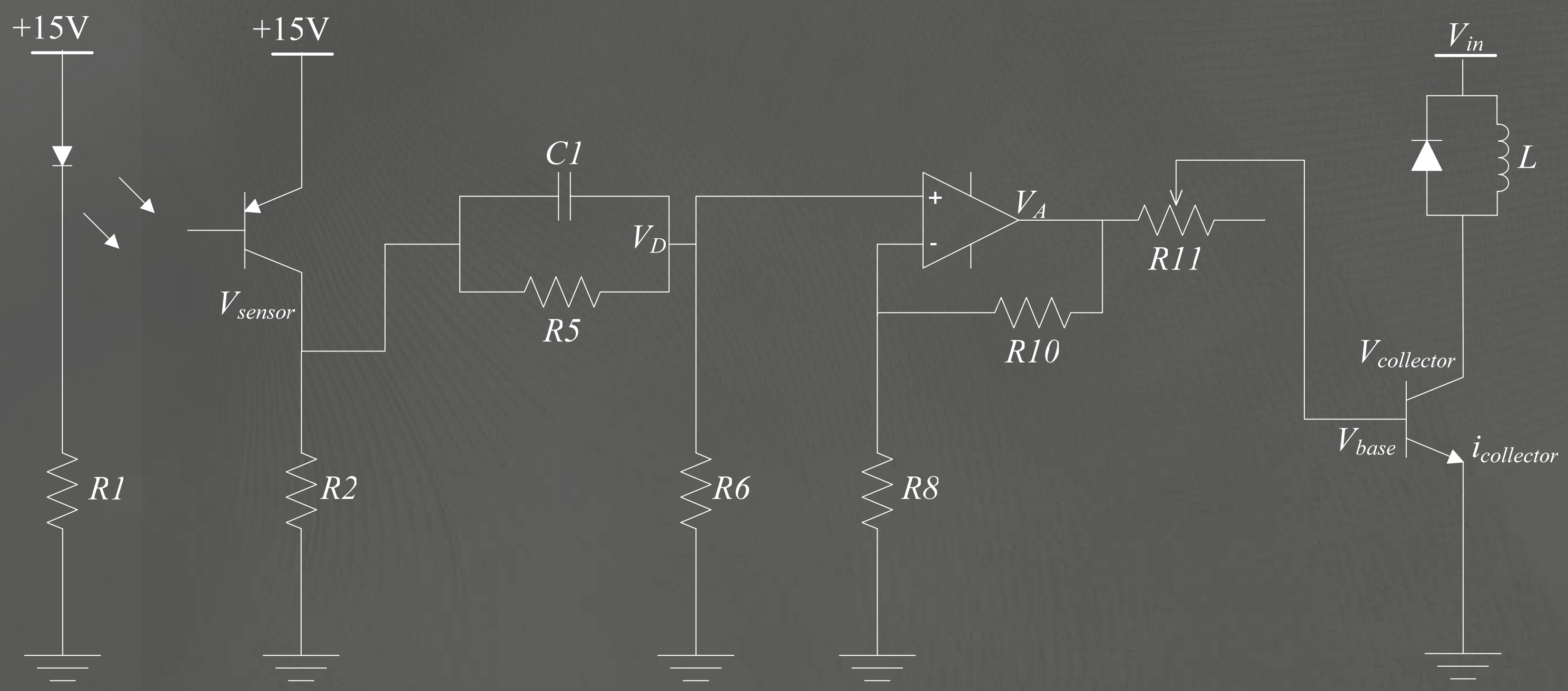
National **I**nstruments'
Educational **L**aboratory **V**irtual **I**nstrumentation **S**uite



Analog Control with NI-ELVIS

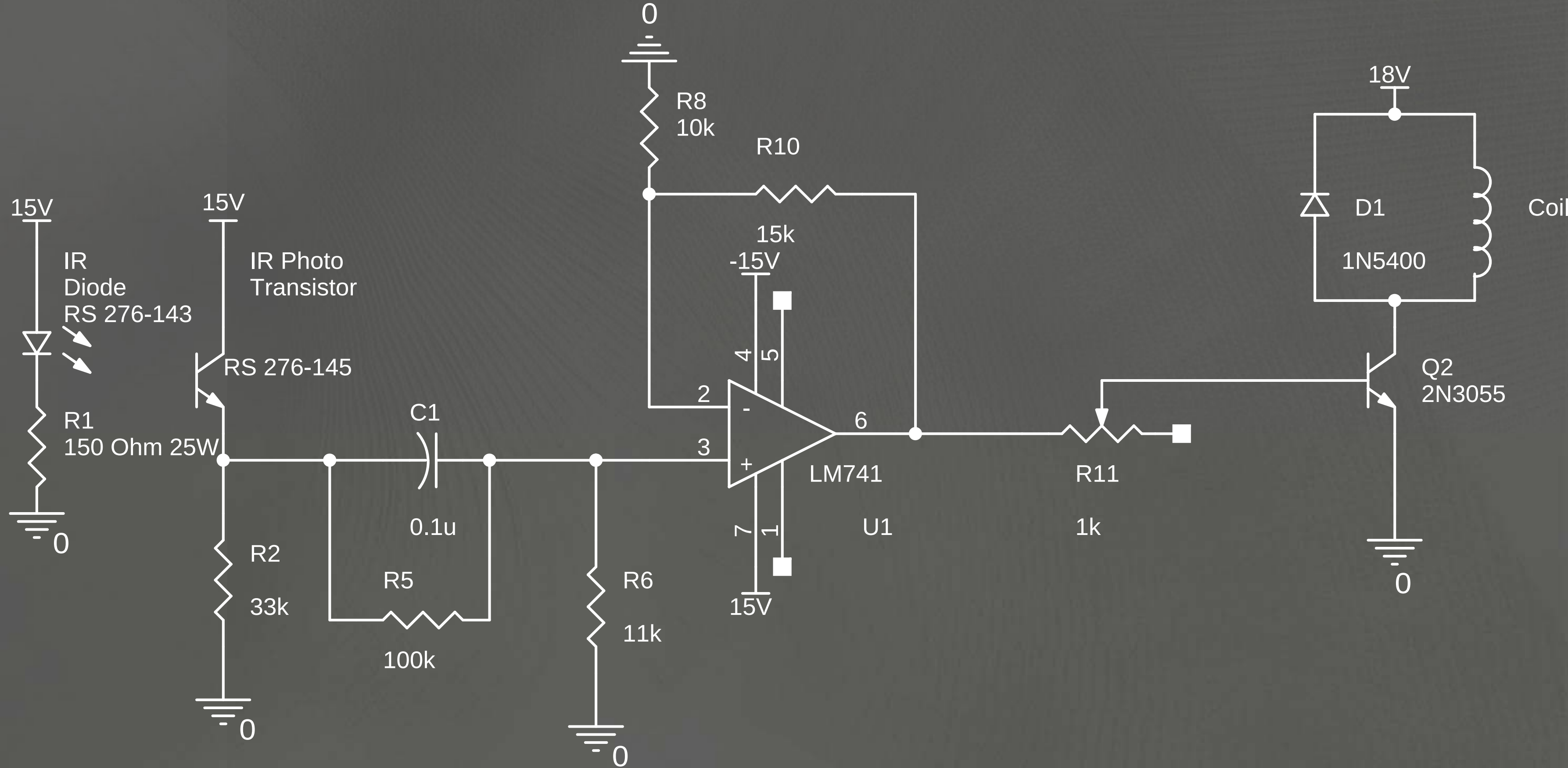


Lead Compensator Analog Circuit

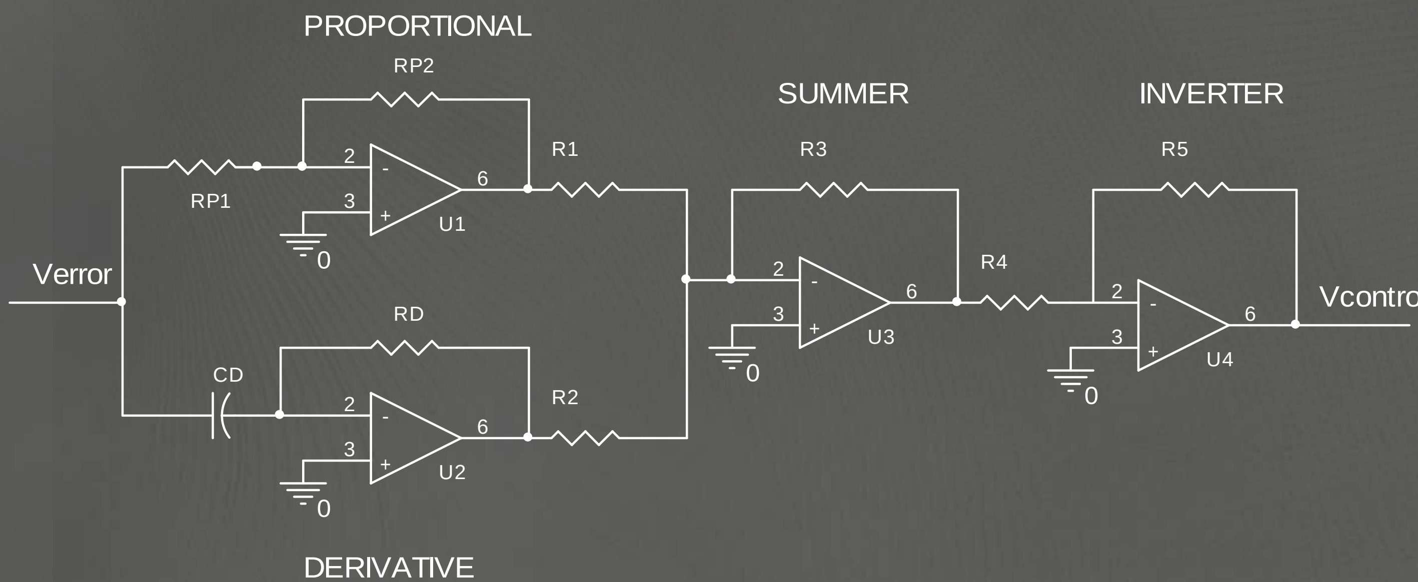


$$G(s) = \frac{V_D}{V_{sensor}} = \frac{s + \dfrac{1}{R_5 C_1}}{s + \dfrac{R_5 + R_6}{R_5 R_6 C_1}}$$

Lead Compensator Analog Implementation

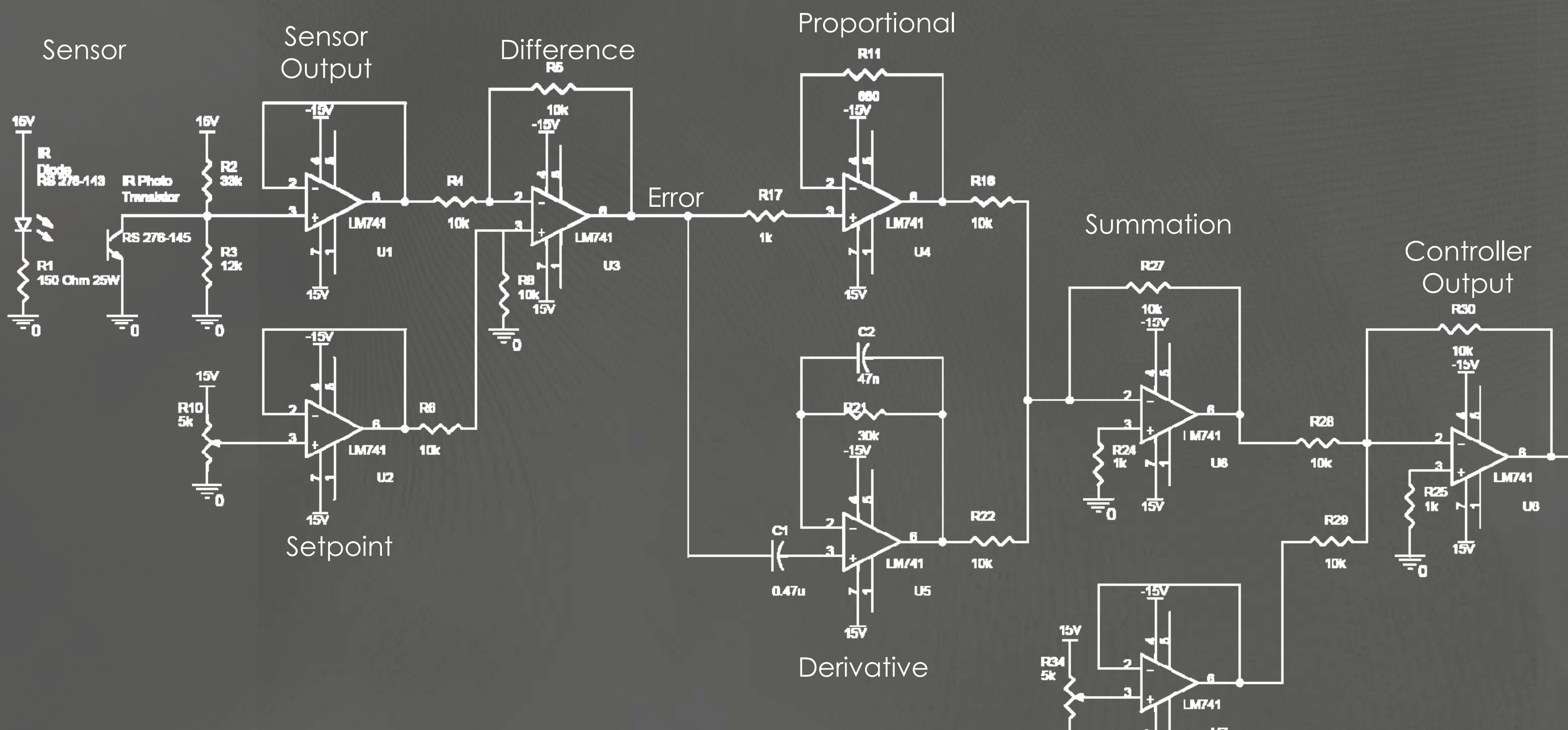


PD Analog Circuit



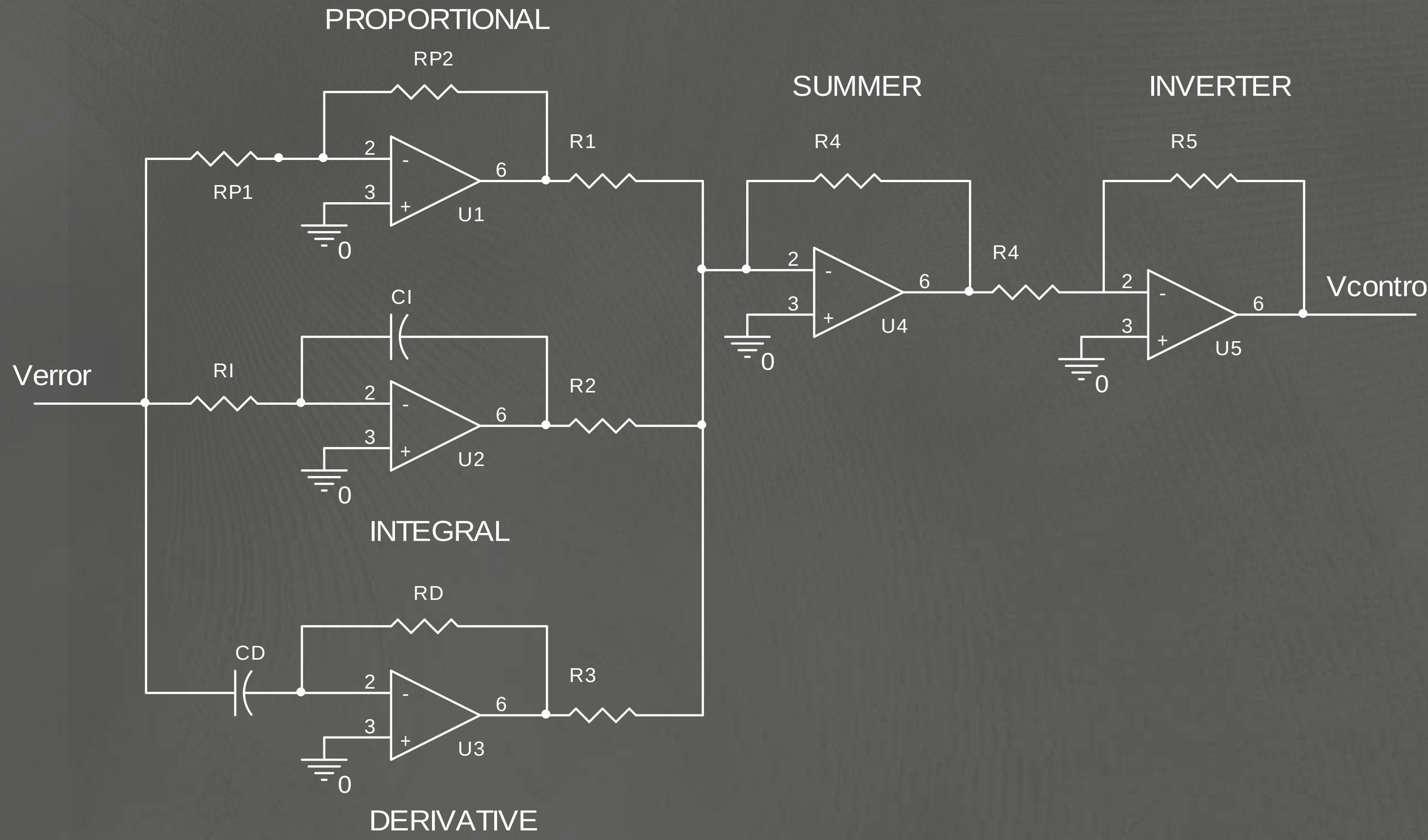
$$G(s) = \frac{V_{control}(s)}{V_{error}(s)} = \underbrace{\left(\frac{RP2}{RP1}\right)}_{K_P} + \underbrace{(RD \times CD)}_{K_D} s$$

PD Analog Circuit Implementation



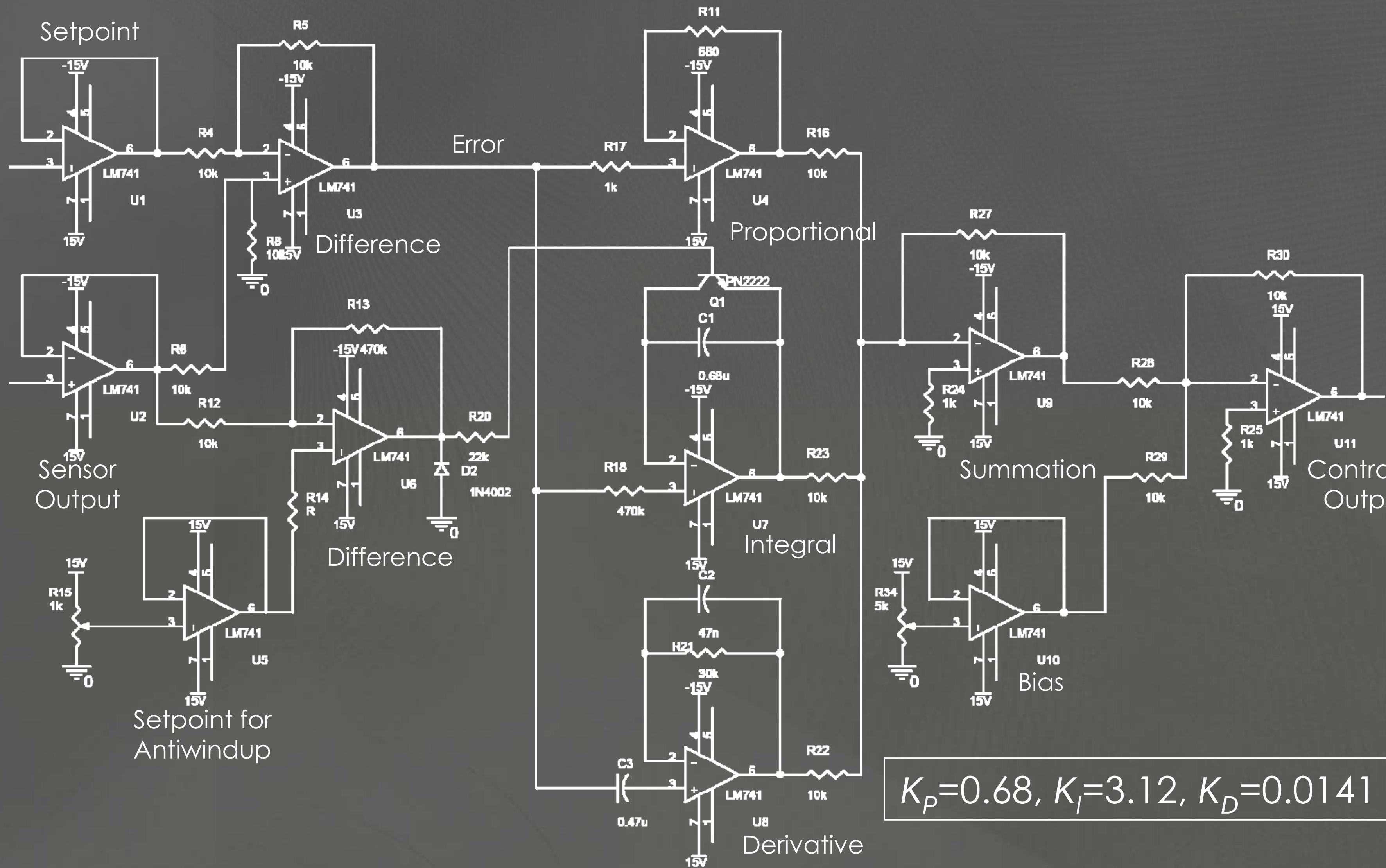
K_P=0.68, K_D=0.0141

PID Analog Circuit



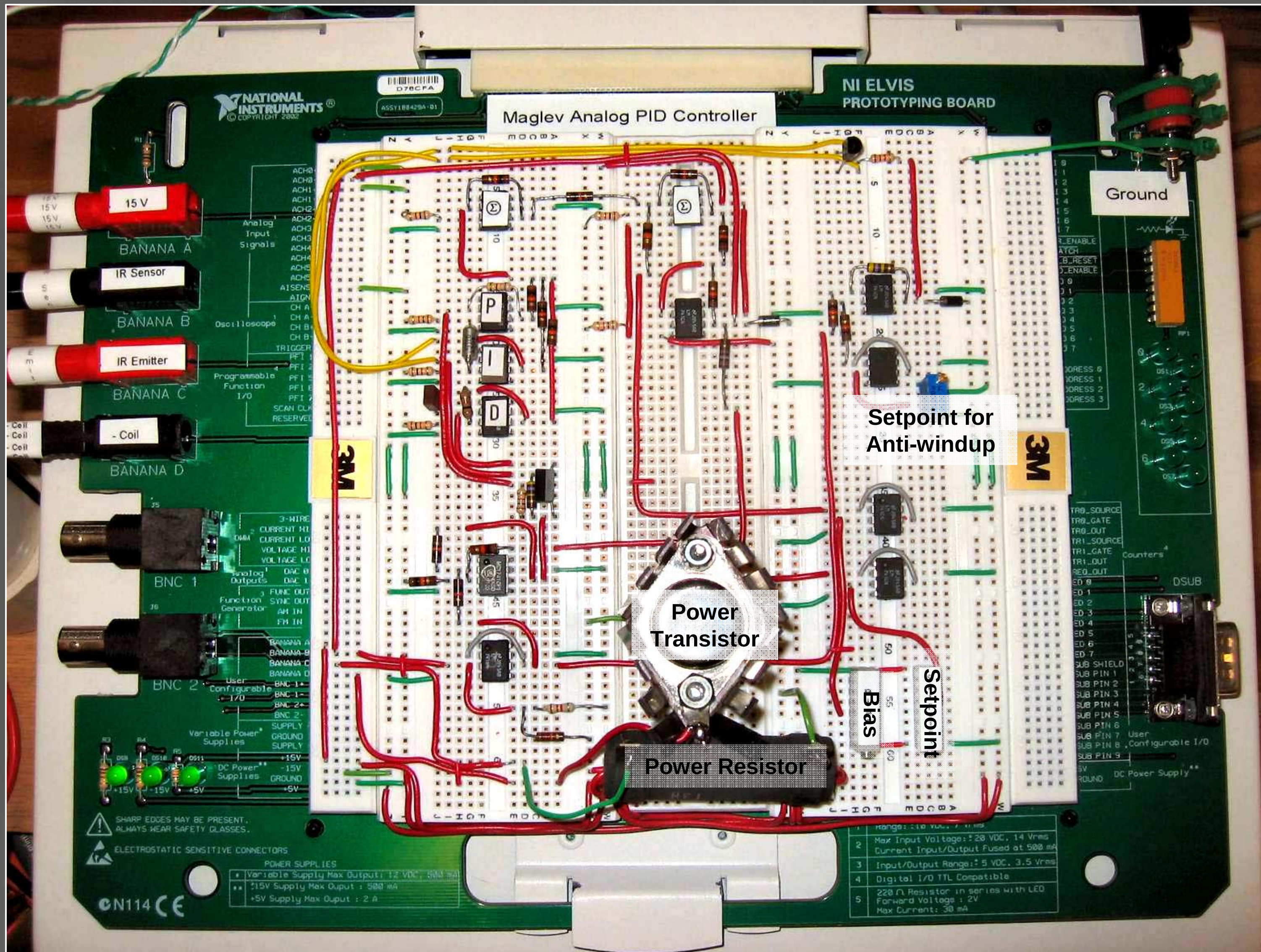
$$G(s)=\frac{V_{control}(s)}{V_{error}(s)}=\underbrace{\left(\frac{RP2}{RP1}\right)}_{K_P}+\underbrace{\left(\frac{1}{RI\times CI}\right)}_{K_I}\frac{1}{s}+\underbrace{(RD\times CD)}_{K_D}s$$

PID Analog Circuit Implementation

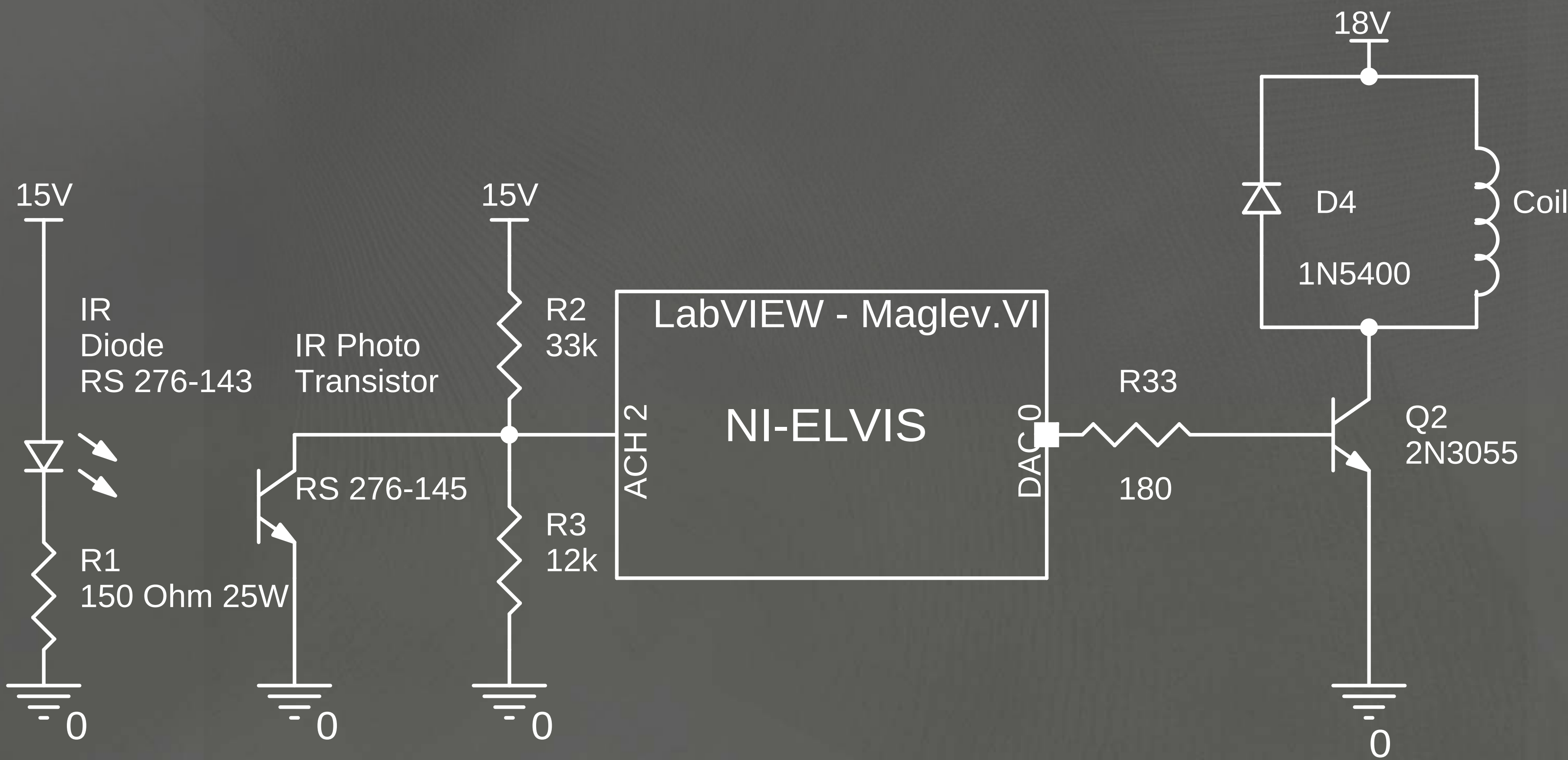


K_P=0.68, K_I=3.12, K_D=0.0141

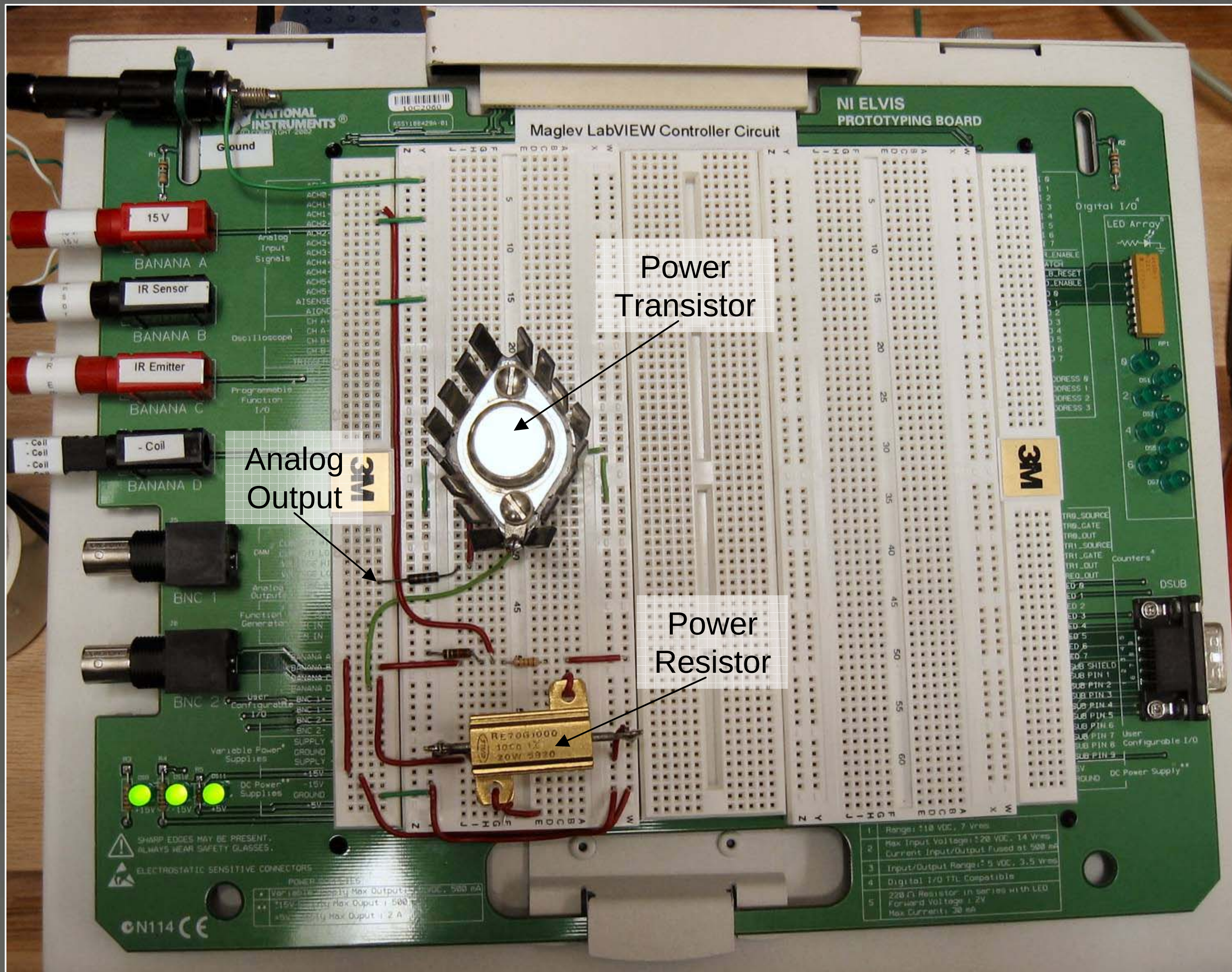
Analog Implementation



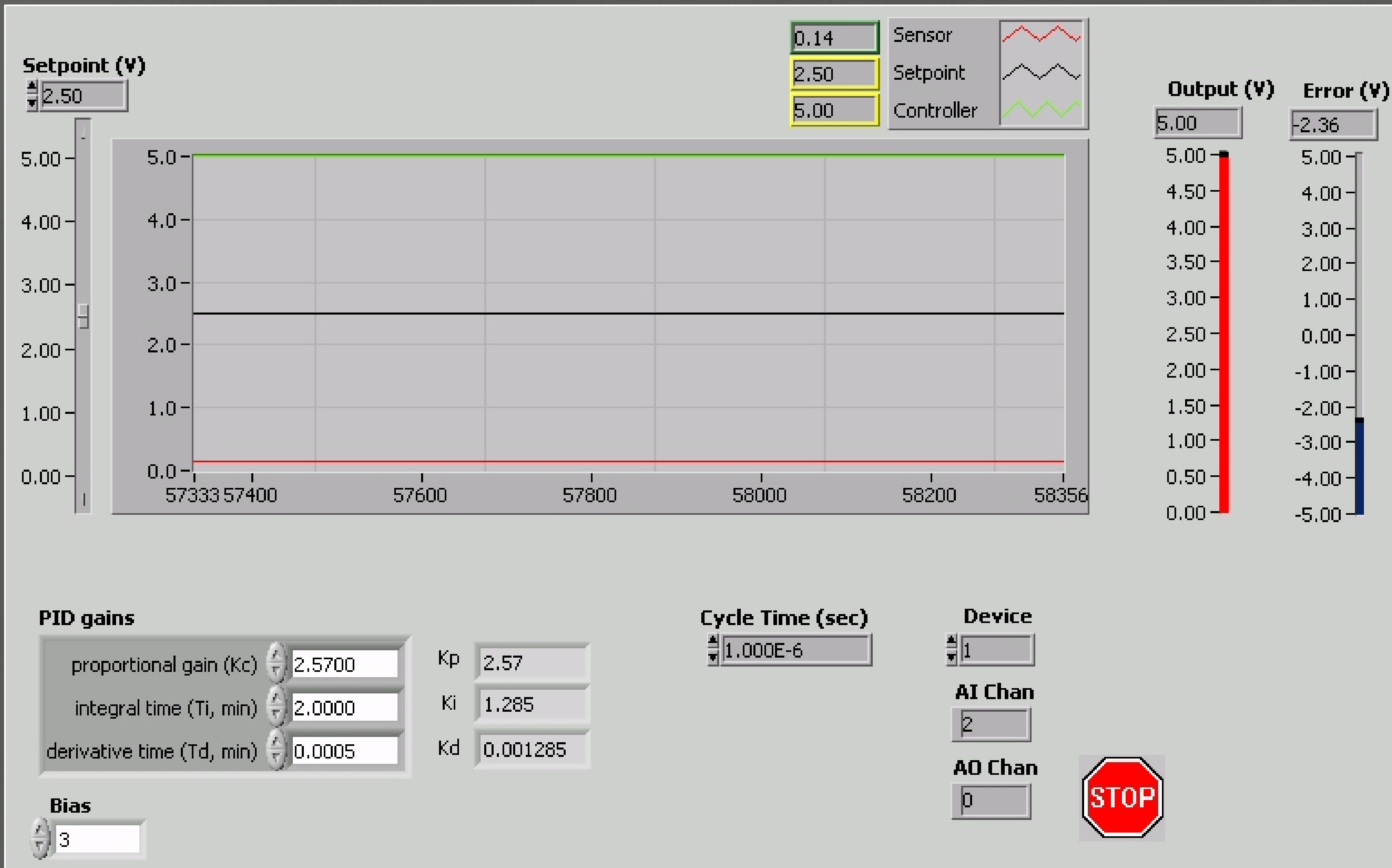
LabVIEW-based Control



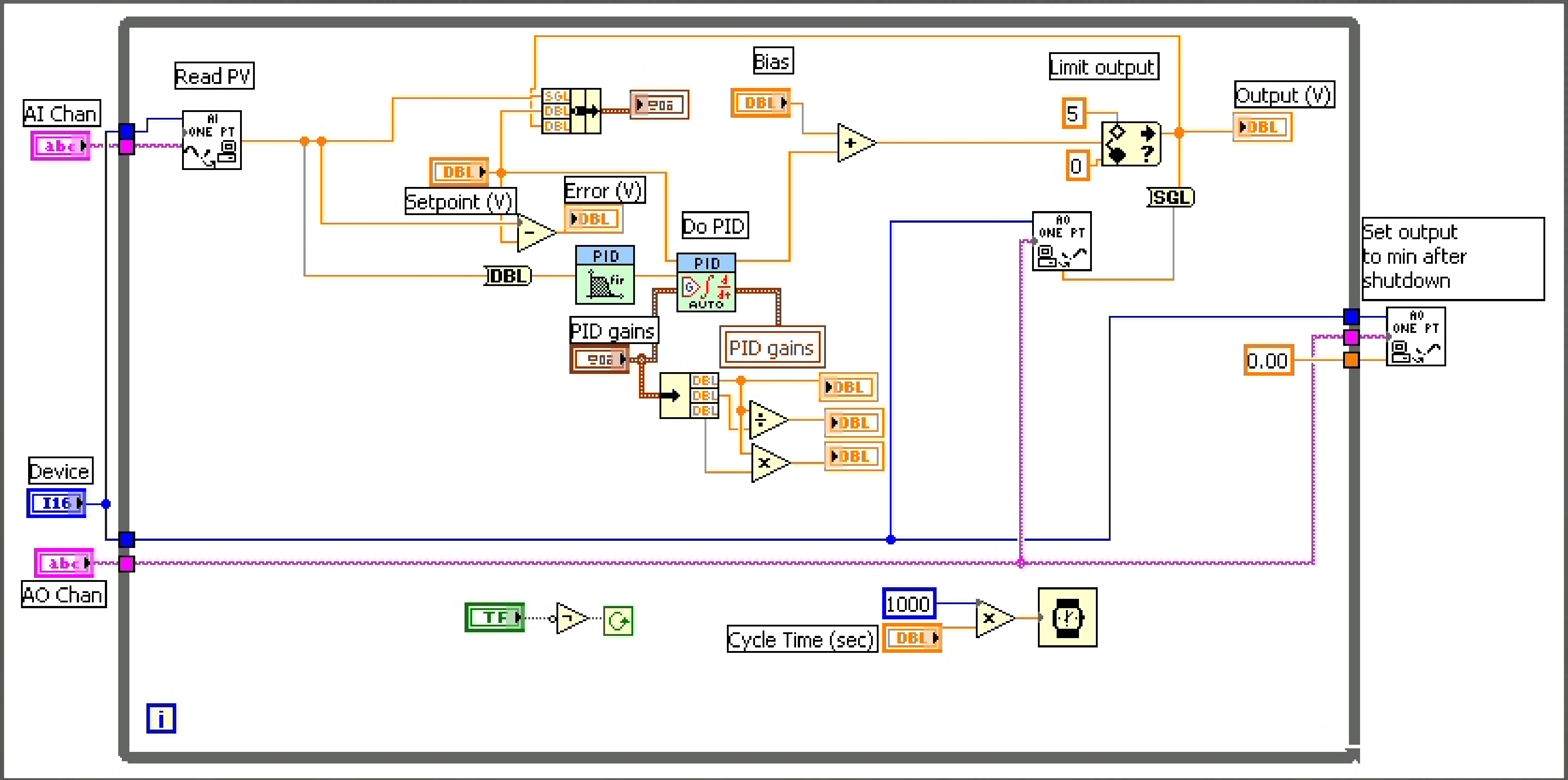
LabVIEW-based Control



LabVIEW VI Front Panel

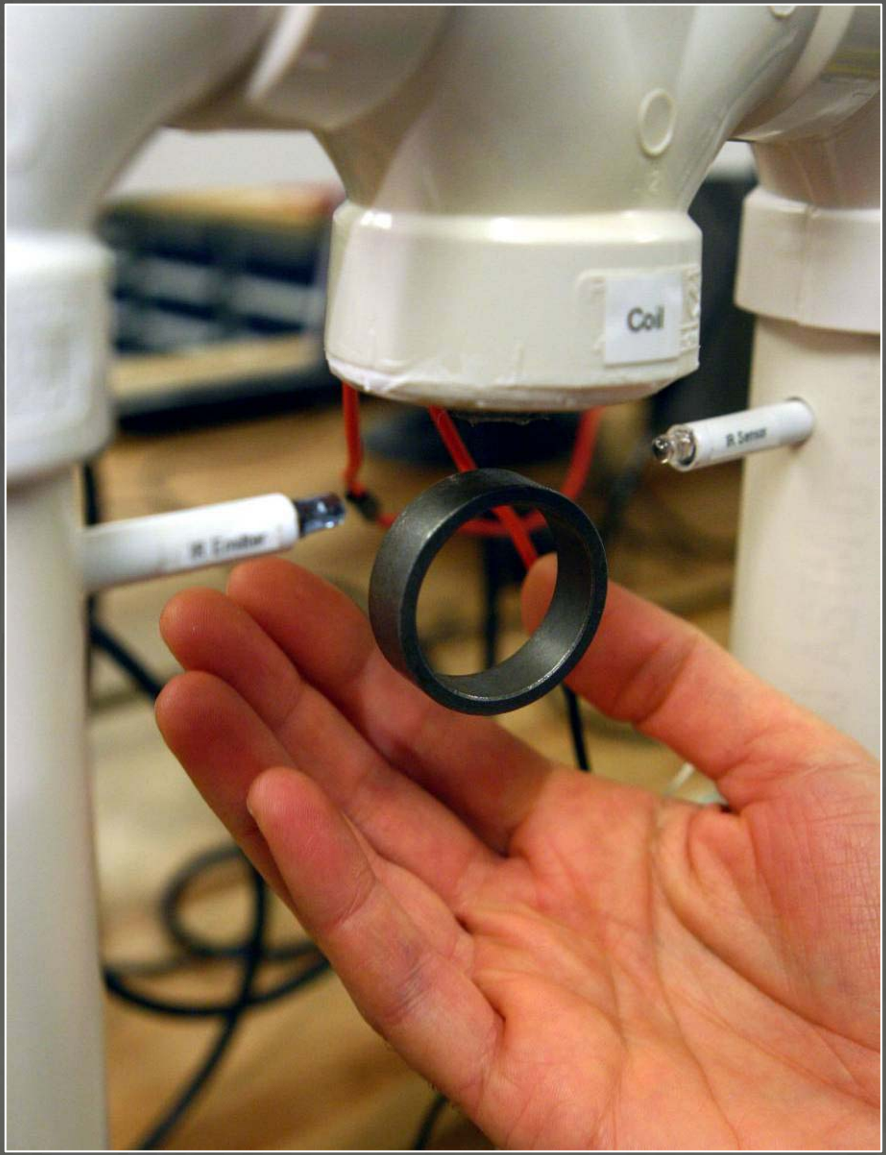


LabVIEW VI Program

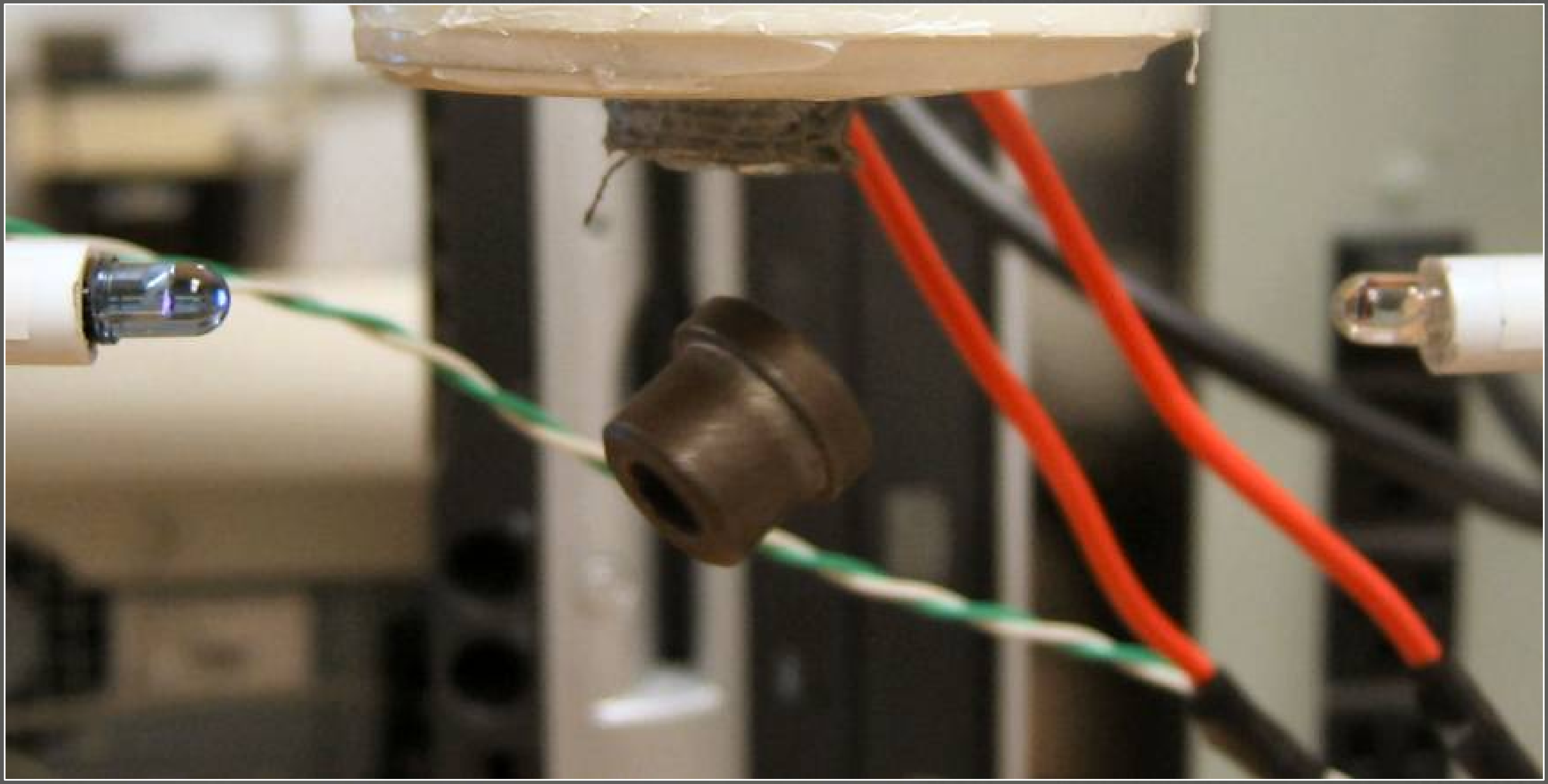


Levitation of AA Battery

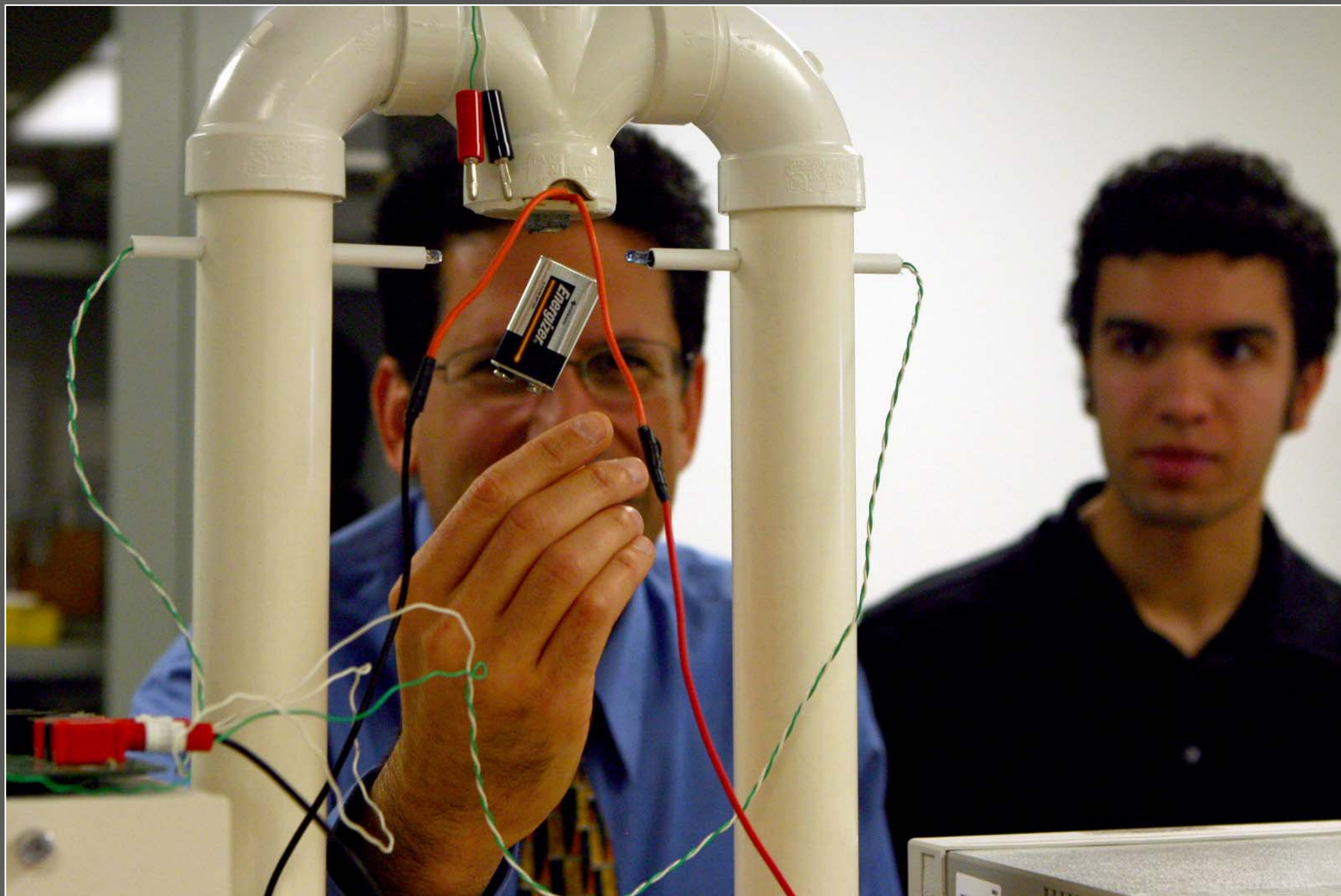
Levitation of Thin Ring



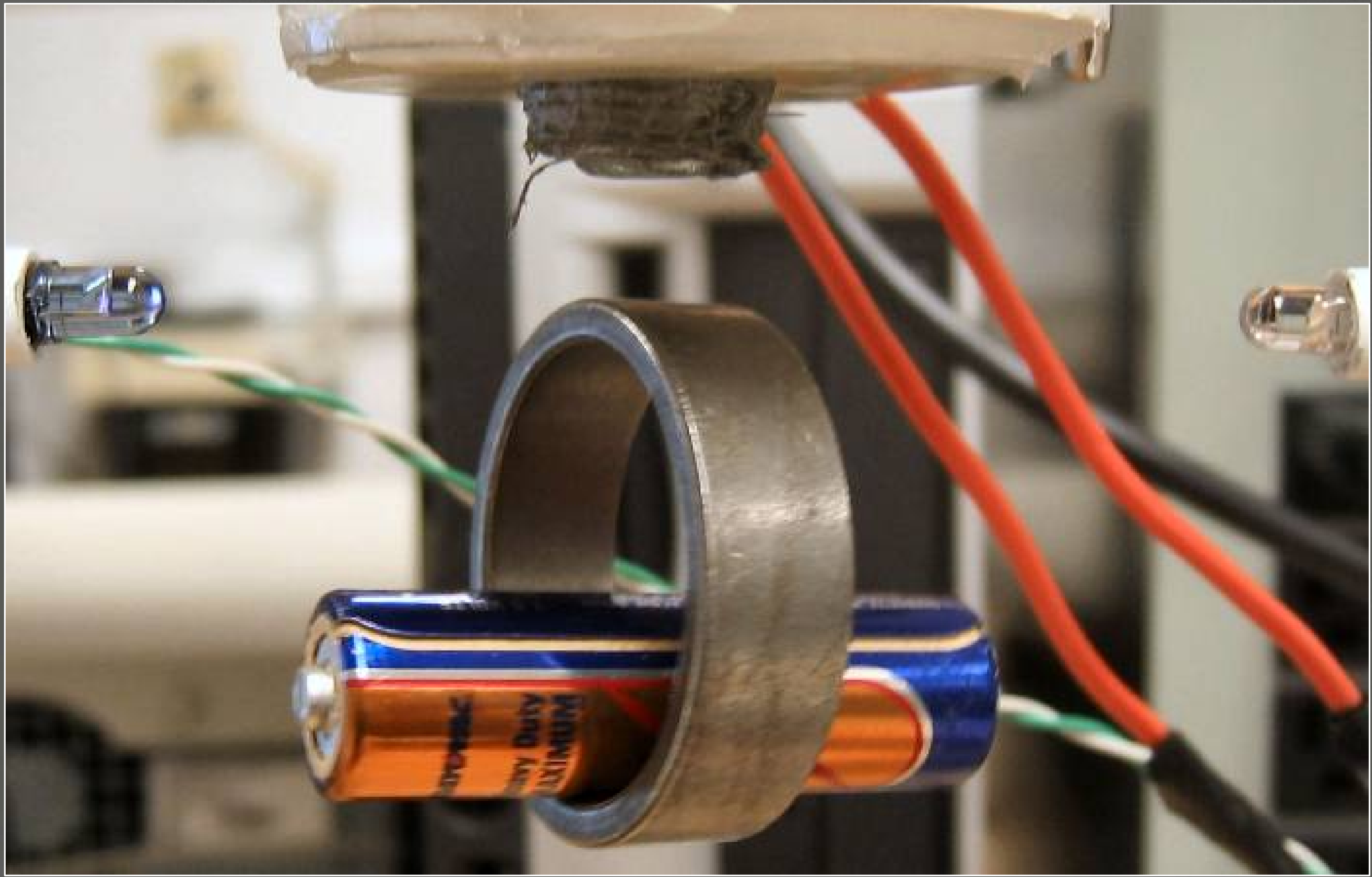
Levitation of Nested Washer



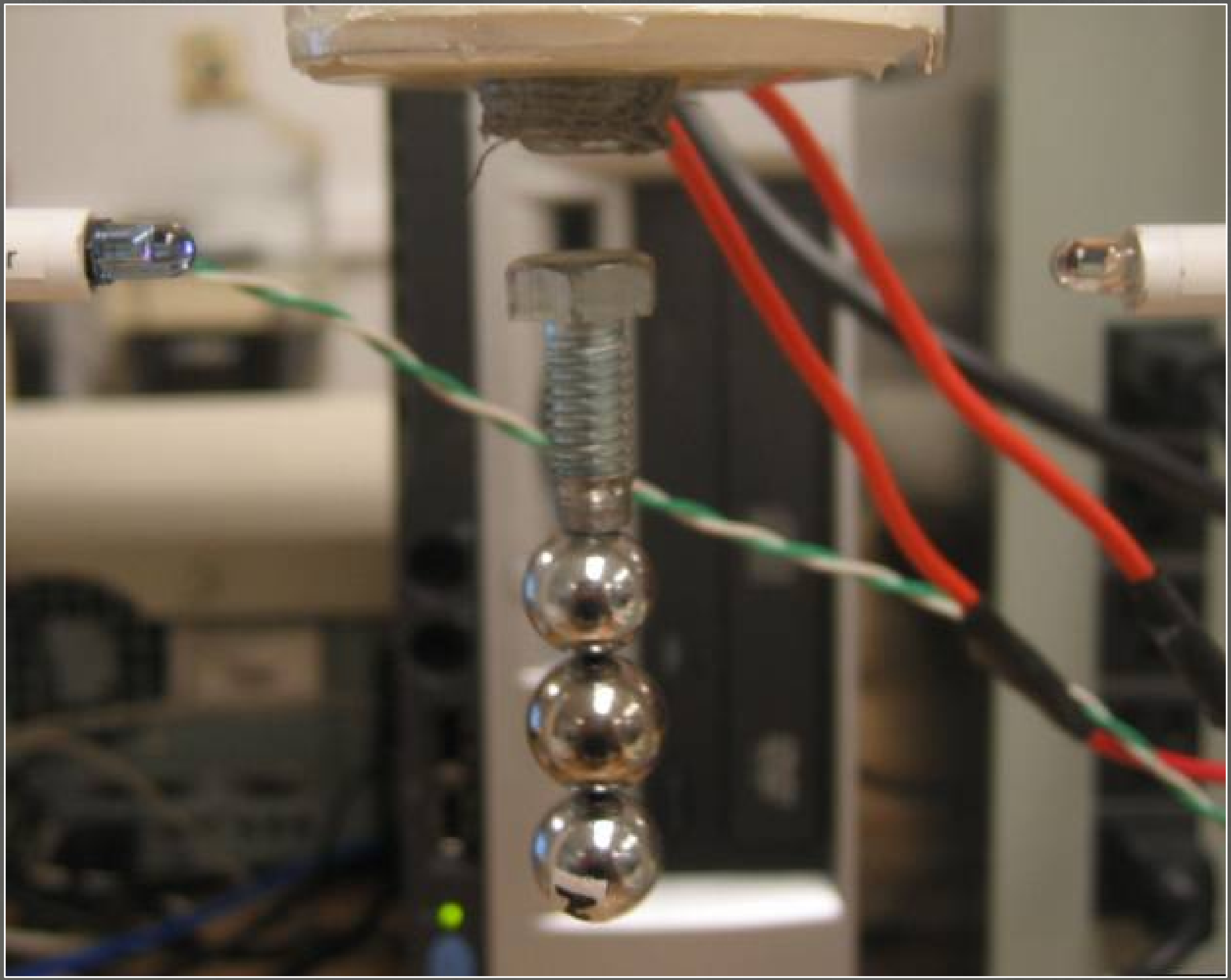
Levitation of 9V Battery



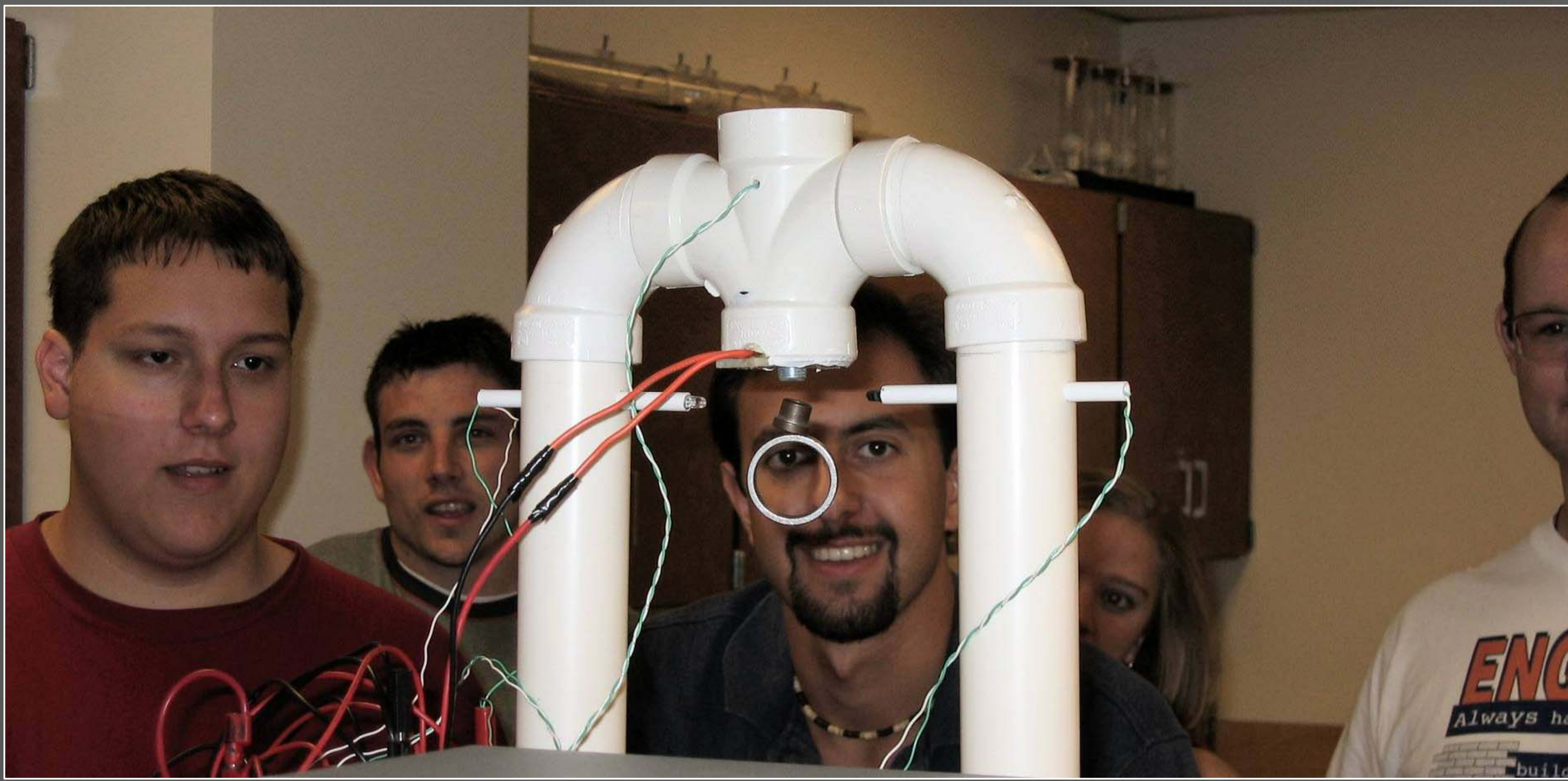
Levitation of Various Objects



Levitation of Various Objects



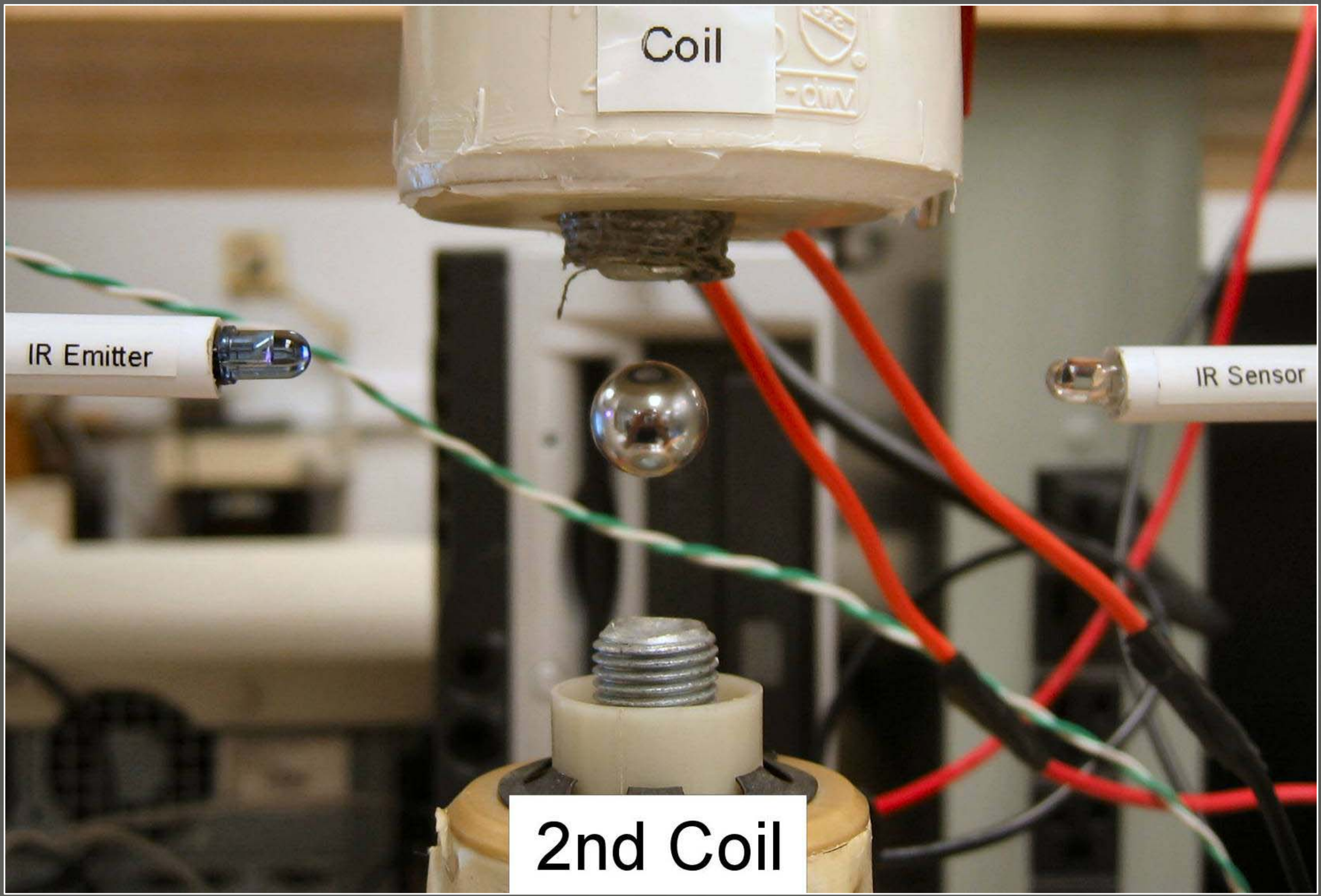
Levitation of Various Objects



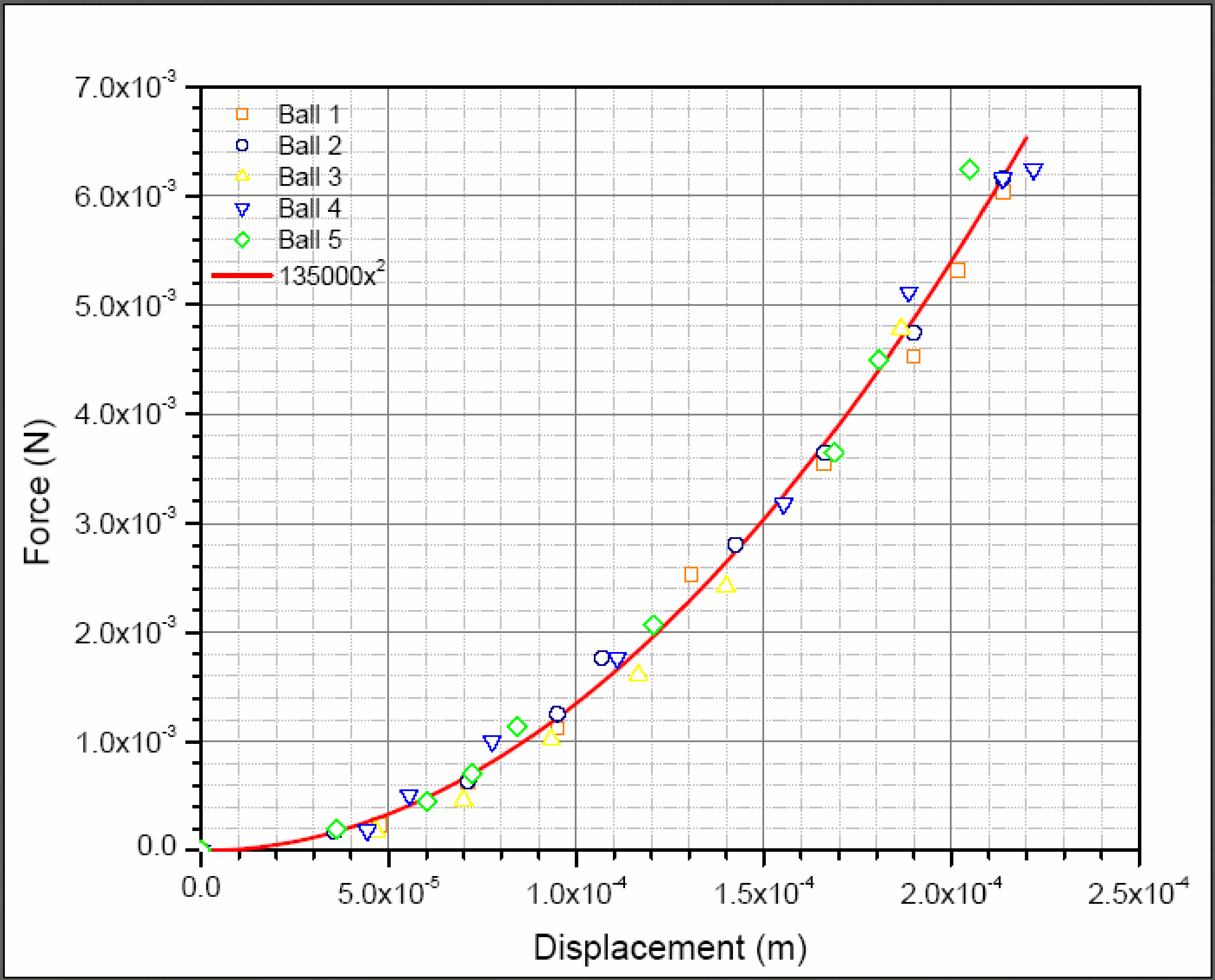
Current Comparisons

OBJECT	MASS (g)	% Variation From 6.8g	CURRENT (A)				
			A -Lead	A - PD	A - PID	LV - PD	LV - PID
Nested Washer	8.94	29.75%	1.34	1.49	1.47	1.49	1.46
Bolt	10.64	54.43%	1.29	1.36	1.32	1.39	1.37
Bolt 2	14.23	106.53%	1.59	1.68	1.60	1.72	1.72
AA Battery	18.89	174.17%	1.16	1.29	1.24	1.30	1.22
Thin Ring	23.49	240.93%	1.27	1.36	1.34	1.37	1.26
Splined Ring	44.27	542.53%	N/A	1.78	1.79	N/A	1.75
9-Volt Battery	47.36	587.37%	N/A	N/A	2.19	N/A	N/A
Large Bolt	50.95	639.48%	N/A	N/A	2.27	N/A	N/A

Addition of Second Coil

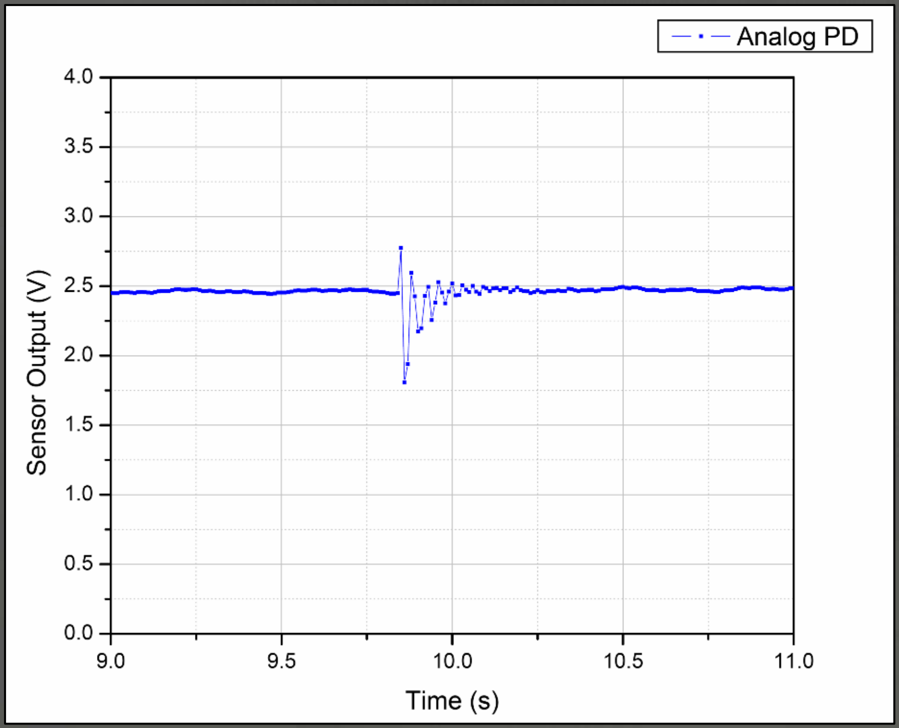


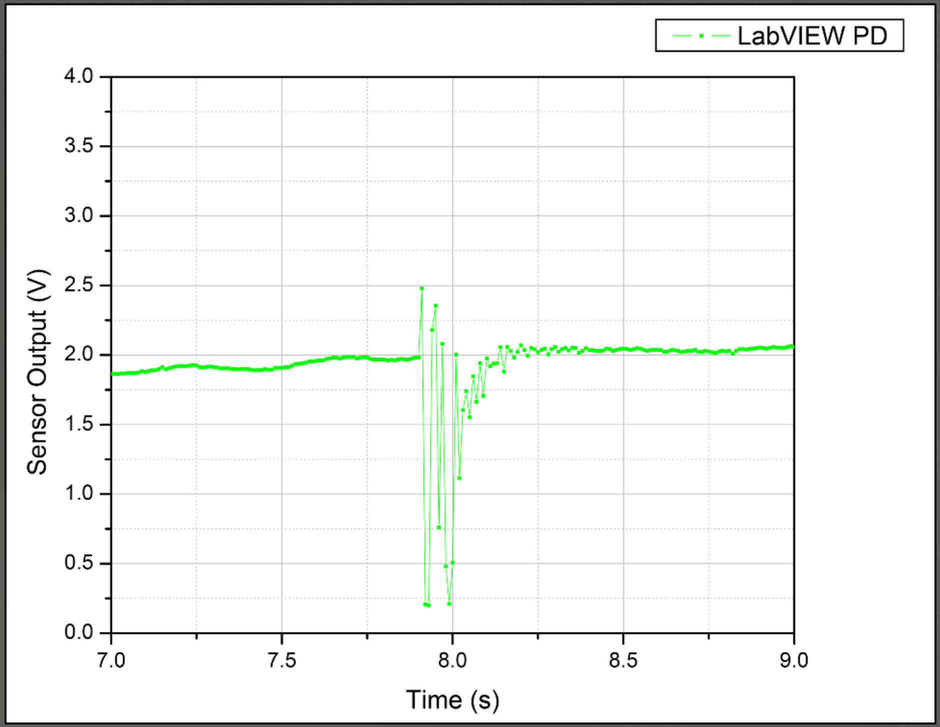
Stiffness



Ball 1
Ball 2
Ball 3
Ball 4
Ball 5
135000x2
7.0x10-3
6.0x10-3
5.0x10-3
4.0x10-3
3.0x10-3
2.0x10-3
1.0x10-3
0.0
Force (N)
0.0
5.0x10-5
1.0x10-4
1.5x10-4
2.0x10-4
2.5x10-4
Displacement (m)

PD Controller Response





Outline of Presentation

- Objectives
- Background
- Maglev Testbed
- Control Strategies
- Simulation Studies
- Experimental Studies
- **Summary**
- **Future Work**

Summary

- Developed nonlinear and linearized model
- Conducted simulation studies to compare controllers and select gains
- Implemented PID-type controllers using analog circuits with NI-ELVIS board
- Developed software-based controllers using LabVIEW
- Compared "hardware" vs. "software" based controllers
- Added second coil for determining stiffness and system response
- Tested practical differentiator and anti-windup circuits

Movie

Closing

- Applied classical linear control strategies to a linearized model of a nonlinear system
- Implemented analog controllers using NI-ELVIS
- Developed LabVIEW controllers
  - Can dynamically change controller type and parameters and observe effect on system in real-time

Outline of Presentation

- Objectives
- Background
- Maglev Testbed
- Control Strategies
- Simulation Results
- Experimental Results
- Summary
- **Future Work**

Future Work

- Implement nonlinear and optimal control strategies in LabVIEW & compare performance with linear control strategies
- Develop a detailed FEA model to optimize the shape of the electromagnet for maximum field strength
- Design an array of sensors to translate levitated object vertically.
- Add horizontal electromagnets for two degree-of-freedom system.

Future Work (cont'd)

- Add velocity sensor for controlled damping
- Develop more advanced model
  - Include gyro-dynamics
  - Include skin friction using a CFD model
- Test remote access to VI through internet
- Create a virtual reality model using Virtual Reality Toolbox
  - Visualization of simulation without actual implementation

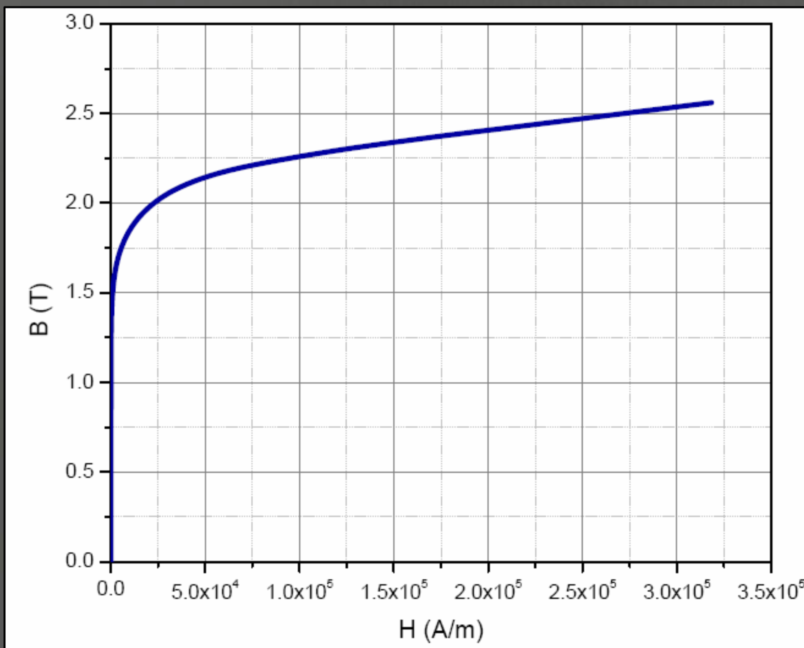
The End

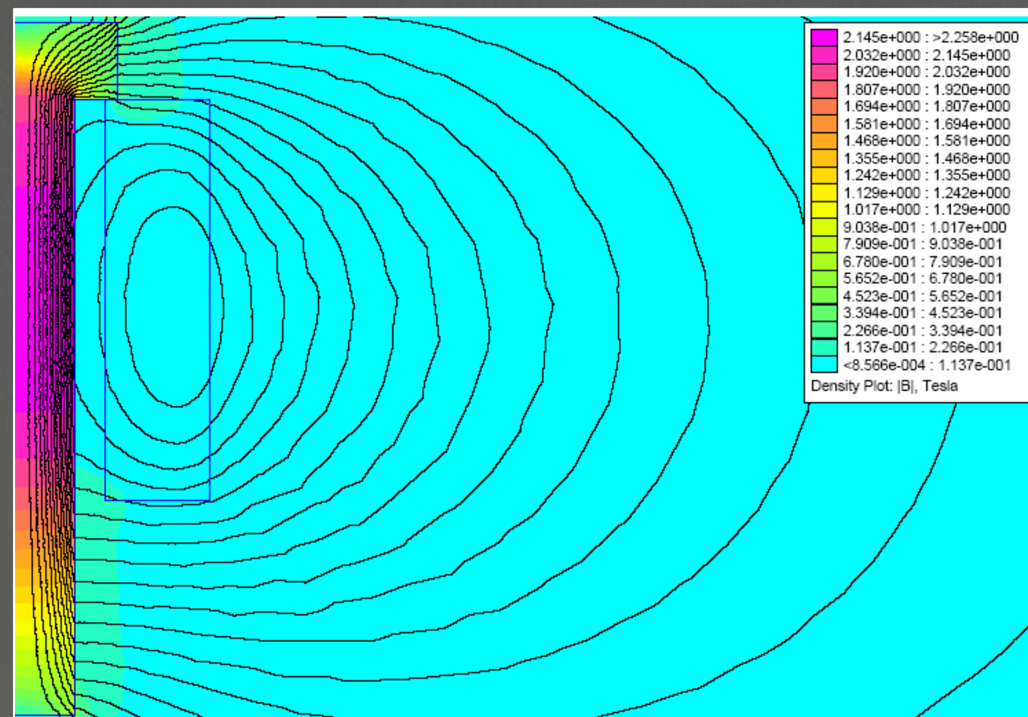
Questions ...

Movie of Levitated Ball

Backup Slides

Magnetic Field FEA Results

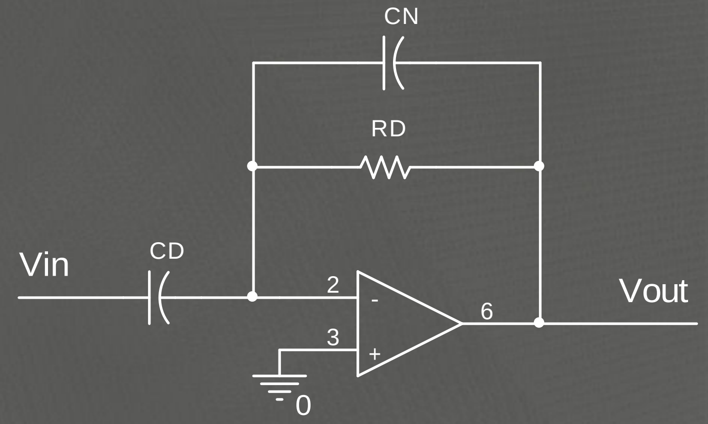




Using FEMM package

Practical Differentiator

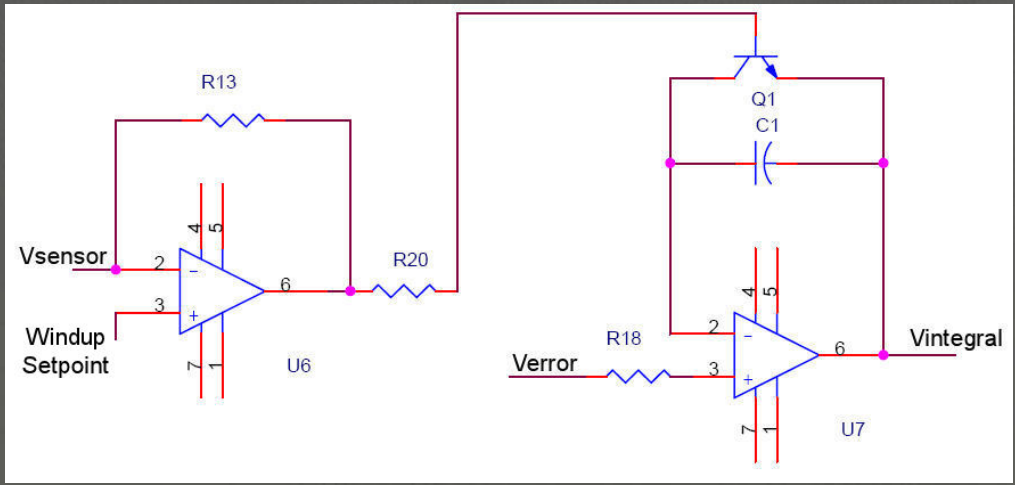
- A pole needs to be added to differentiator circuit for "roll-off" of high frequency response.
- Without additional pole, differentiator circuit just amplifies any high frequency noise signals.
- Need to filter high frequency signals from signal going to the differentiator.
- Capacitor, CN, added in the differentiator circuit



$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{(RD)s}{(RD \times CN)s + 1}$$

Anti-windup Circuit

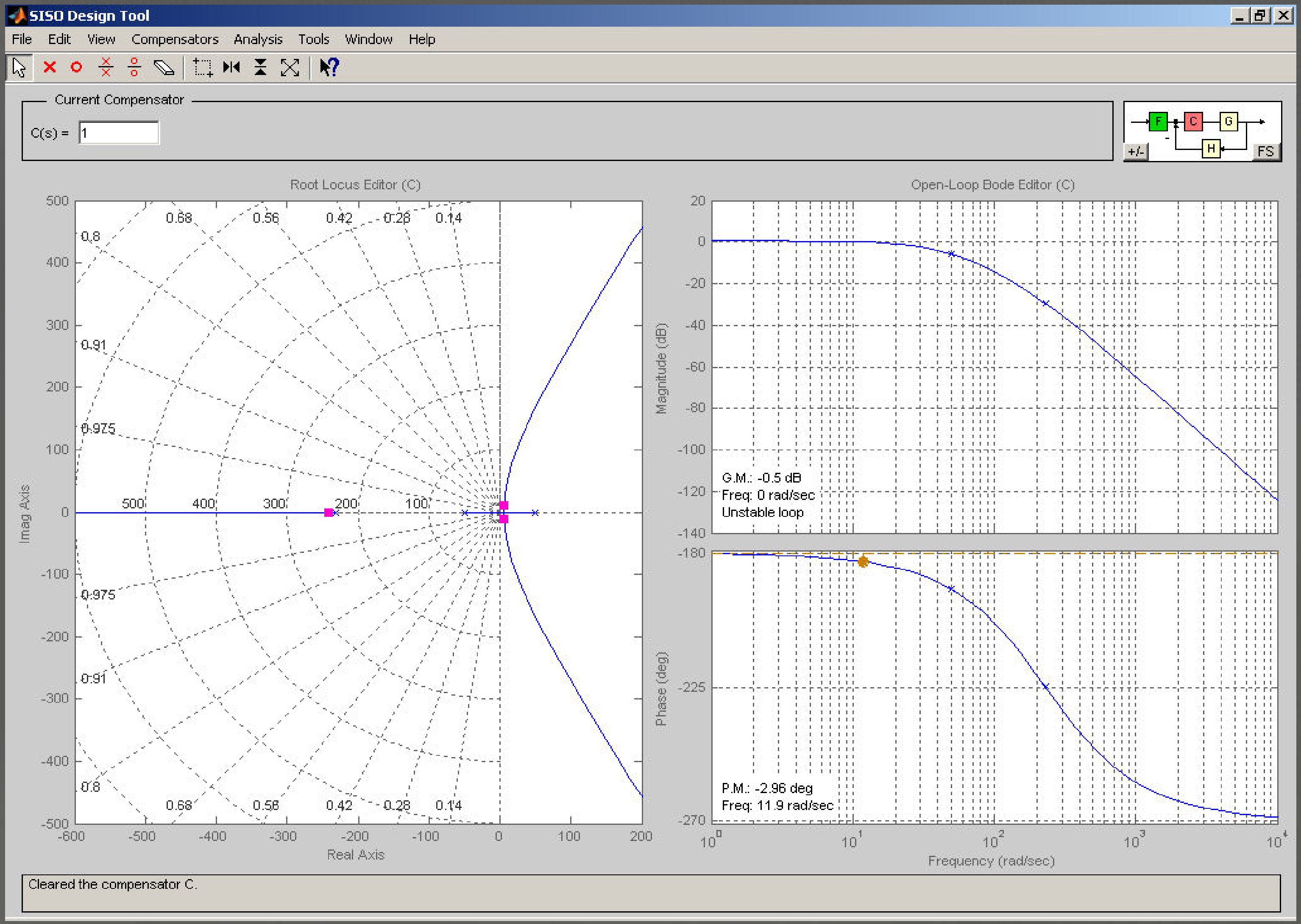
- The integral circuit integrates the error with respect to time
- If error is large & constant, e.g., when the object is not present, integral action will continuously increase until saturation
- Need an “anti-windup” circuit



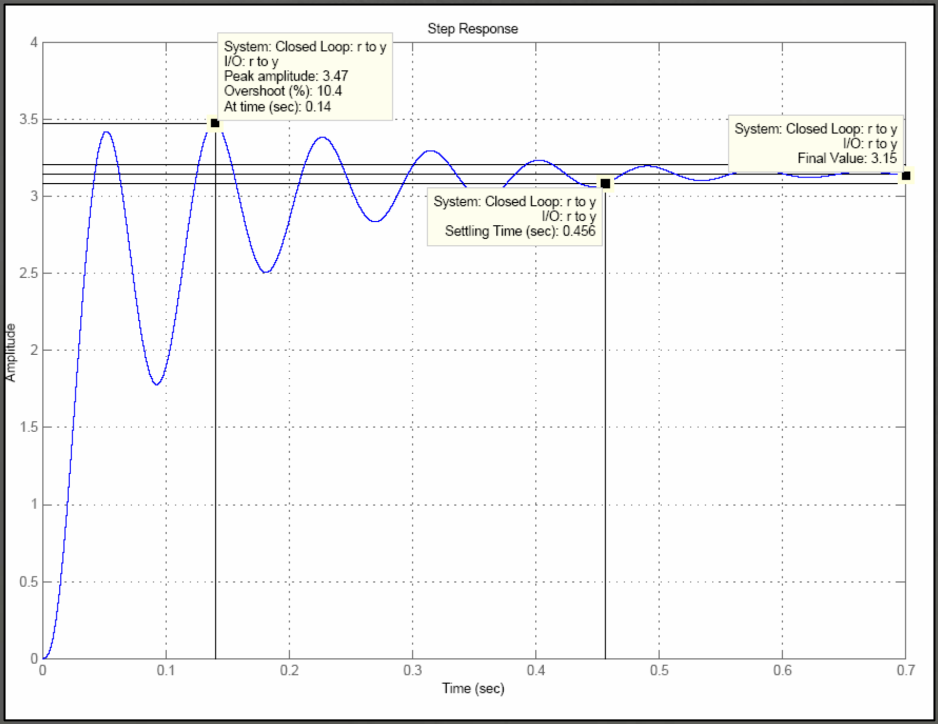
System Identification

SYMBOL	DESCRIPTION	SI UNITS
m	Mass of the object	kg
x_o	Equilibrium distance	m
V_{in}	Voltage supplied to electromagnet	V
i_o	Equilibrium current	A
C	Force constant	$N\text{-}m^2/A^2$
R	Coil resistance	Ω
L	Coil inductance	H
β	Sensor gain	V/m
β_F	Transistor constant	

SISO Design Tool

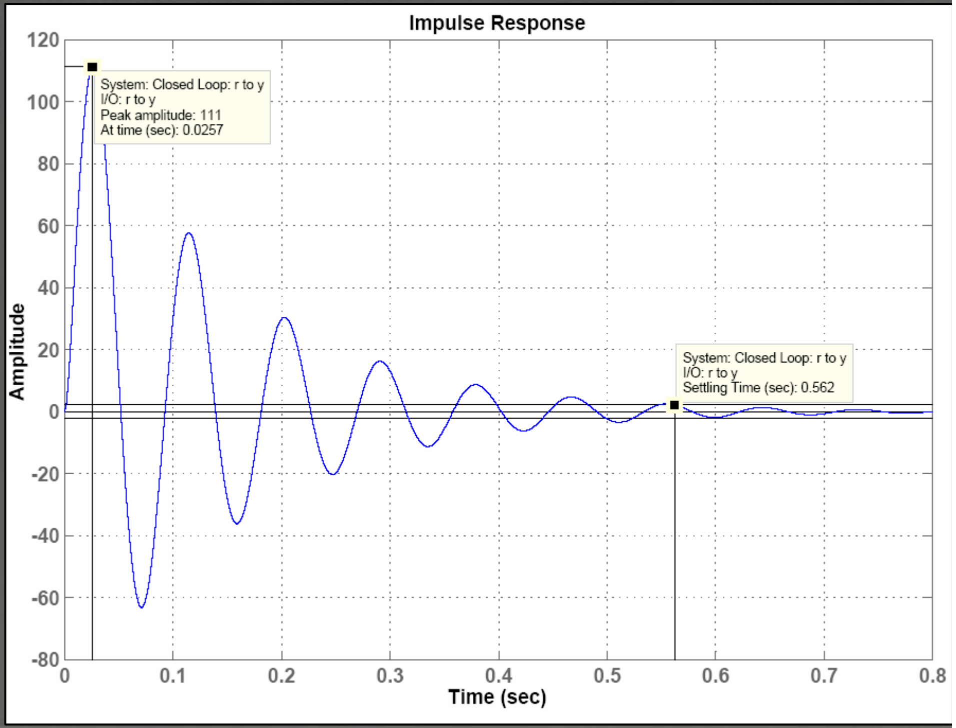


PD Controller Response



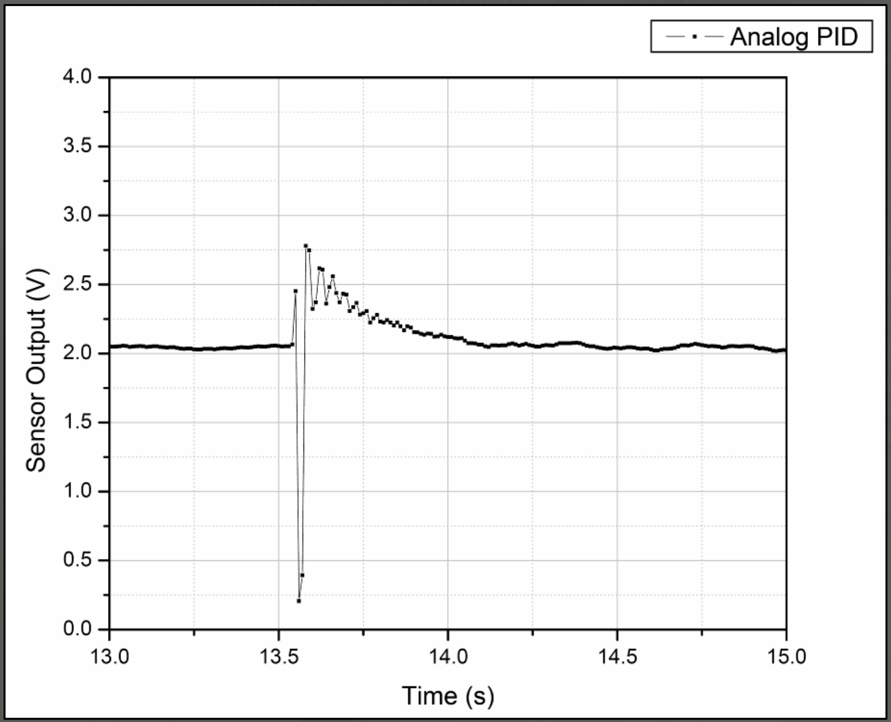
Step Response
Settling Time: 0.157s
Steady-State Error: 2.15

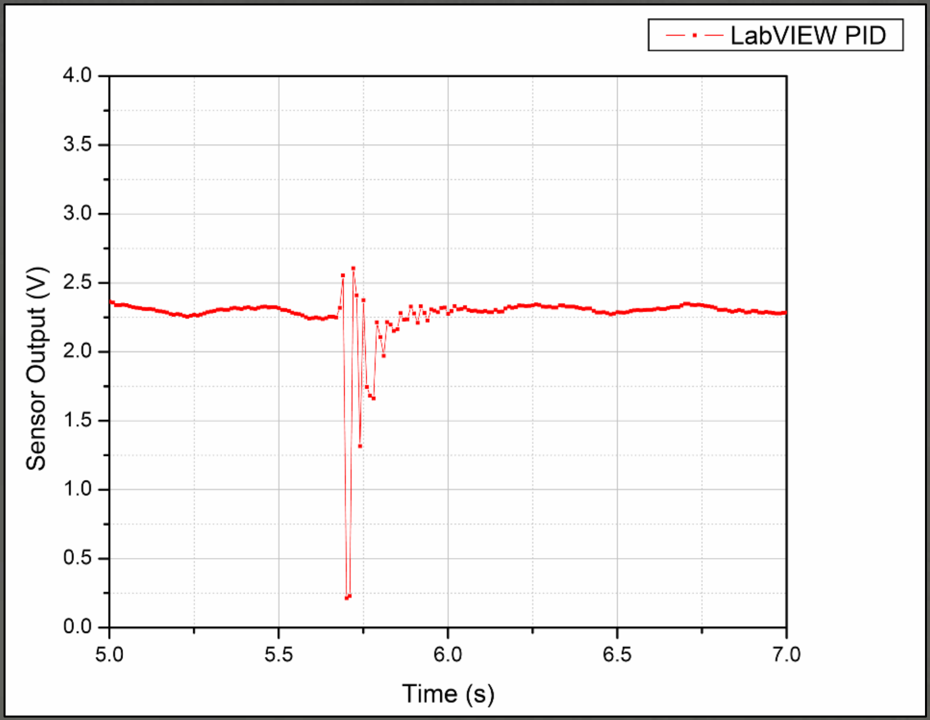
(K_P=0.68, K_D=0.0141)



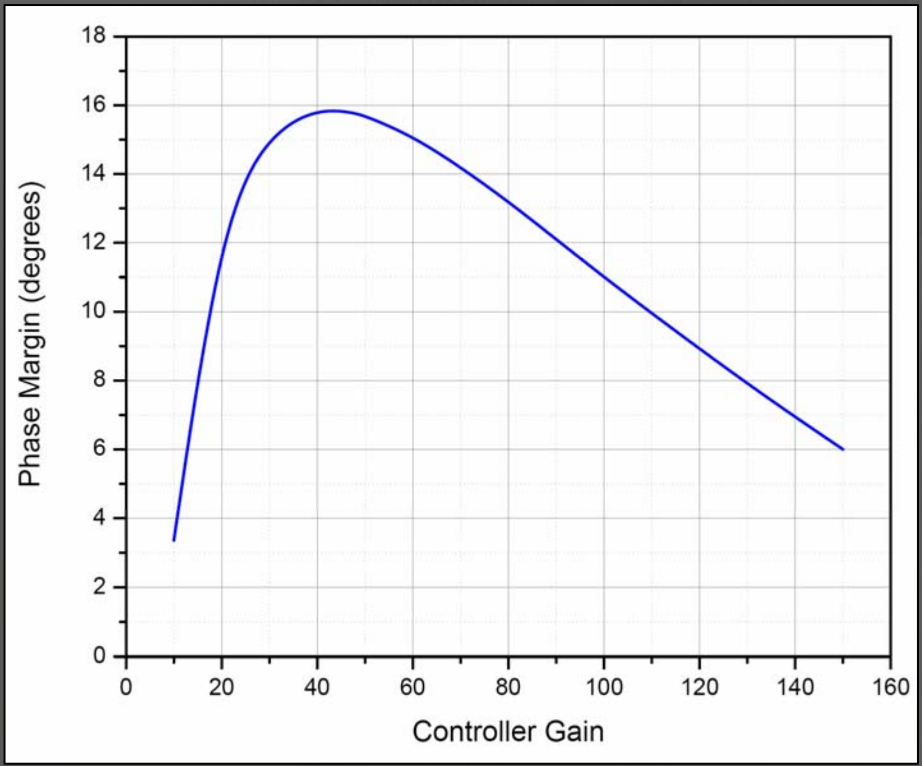
Impulse Response
Settling Time: 0.562s

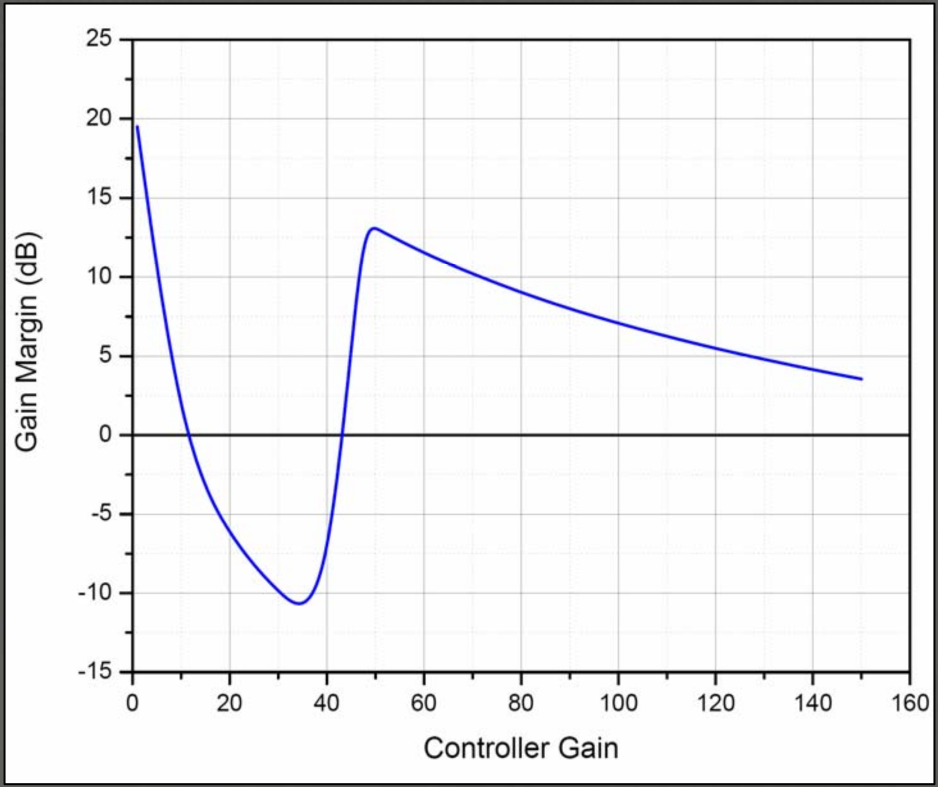
PID Controller Response





Margin Plots for PD Controller





Margin Plots for PID Controller