Electromechanical Engineering Systems for 2nd-Year Students

Modeling, Analysis, Measurement, & Control

Electrical, Mechanical, & Electromechanical Systems

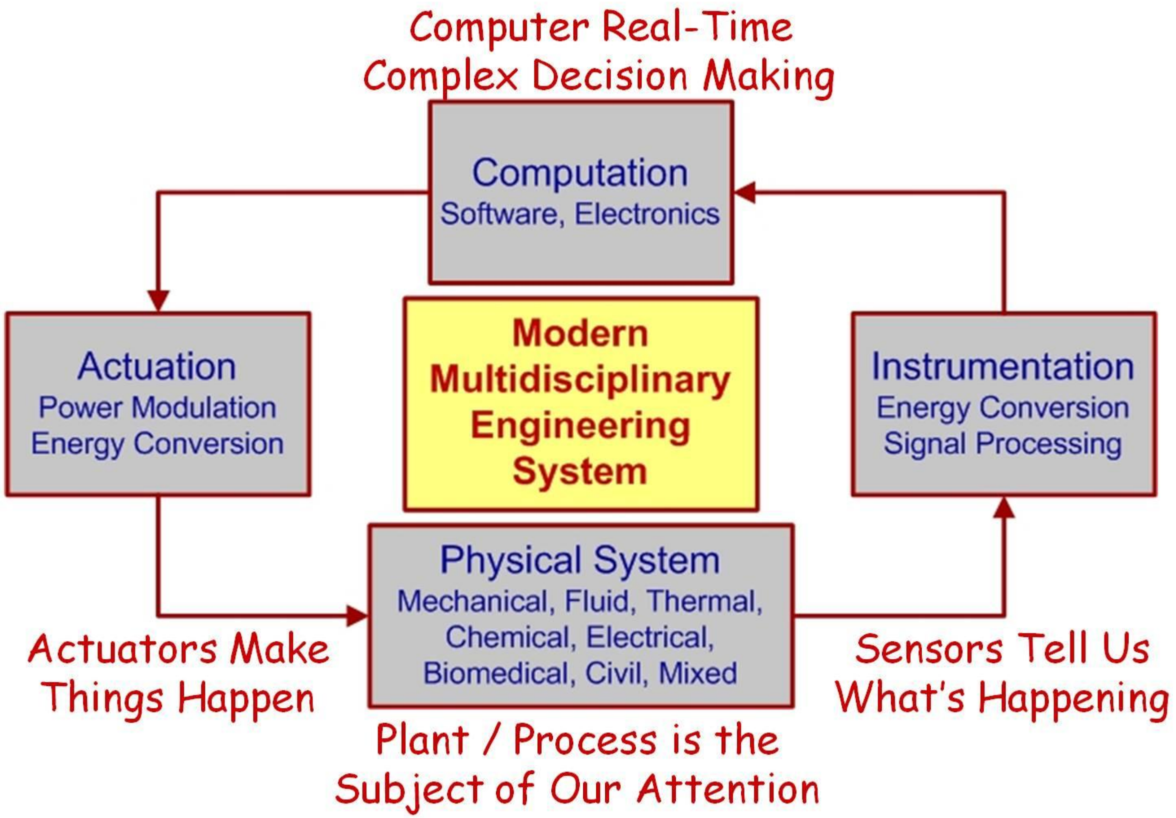
Theory & Implementation

Analog & Digital

Integrated & In-Context

Real-World Examples

Hands-On Studios coupled to Interactive Classes



Why Is This Course Needed?

- Purpose: **Integration with Context**
  - This course, and the junior-level course that follows, **integrates** the essential content found in several traditional engineering courses: electric circuits, measurement systems, modeling & analysis of dynamic systems, actuators, control systems & control system implementation.
  - It presents material in an **integrated way in the context of modern engineering systems**. It makes connections to the other courses the sophomores are taking in differential equations, physics (electricity & magnetism), and dynamics.
- Major Challenge: **Get Students To Critically THINK!**
  - Get students to **think** and see how this knowledge and skills need to come together to design and implement engineering systems. **See the big picture** and not just focus on details and grades. Get them to **take ownership** of their education.

Course and Studio Details

- What and Who
  - MEEN 2210, 3 credits, required 2nd-year ME course
  - 60 Mechanical Engineering Sophomores
- Format
  - Three 50-minute class sections twice a week (M/W 2-5)
  - Five 50-minute studio sessions twice a week (T/Th 8-1)
  - Taught by K. Craig – all classes and all studio sessions for the full studio time period, plus 8 office hours each week (M/W 1-2, T/Th 2-5). Total Faculty Hours per week = 24
  - 2 teaching assistants who only grade; no student contact. Each week there is a Monday class quiz, a Tuesday studio quiz, and Wednesday the weekly problem set is due.

MEEN 2210 Spring Schedule

MEEN 2210 Spring 2011

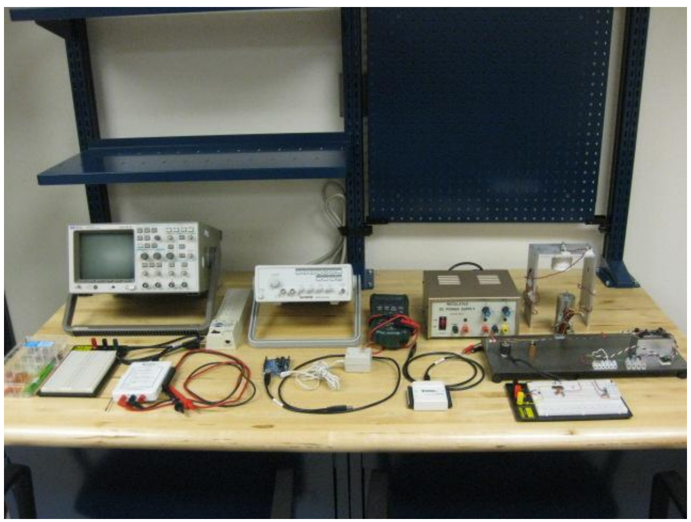
Date	Monday	Tuesday	Wednesday	Thursday
1/17	No Class Quiz #	Studio 1 Quiz #	1 # Problem Set	2
1/24	2 #1	3 #1	3 #1	4
1/31	4 #2	5 #2	5 #2	6
2/7	6 #3	7 #3	7 #3	8
2/14	8 #4	9 #4	9 #4	10
2/21	10 #5	11 #5	11 #5	12
2/28	12 #6	13 #6	13 #6	14
3/7	14 Review	15 Review	15 Midterm Exam	16 Midterm Exam
3/14	No Class	No Studio	No Class	No Studio
3/21	16	17	17	18
3/28	18 #7	19 #7	19 #7	20
4/4	20 #8	21 #8	21 #8	22
4/11	22 #9	23 #9	23 #9	24
4/18	24 #10	25 #10	25 #10	No Studio
4/25	26 #11	26 #11	27 #11	27
5/2	28 #12	28 #12	29 #12	29

MEEN 2210 Final Exam Wednesday, May 11, 2011 3:30-5:30 PM

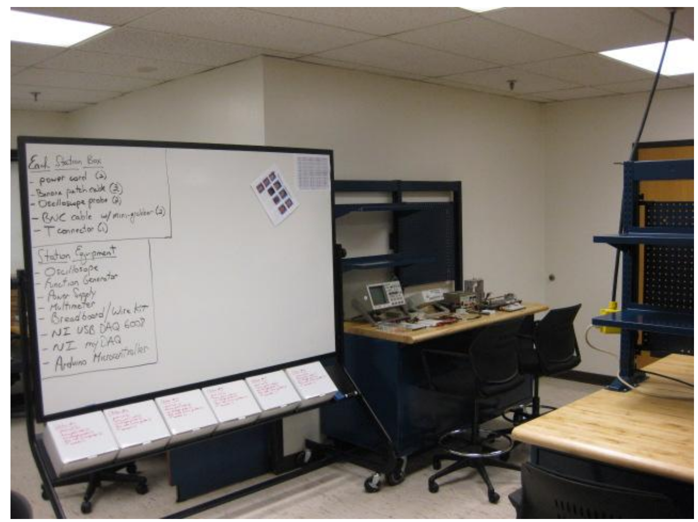
Electromechanical Engineering Systems Studio

Room 310

Studio Equipment



Two-Person Studio Station



6 Two-Person Stations

Electromechanical Engineering Systems Two-Person Studio Station

Analog Function Generator

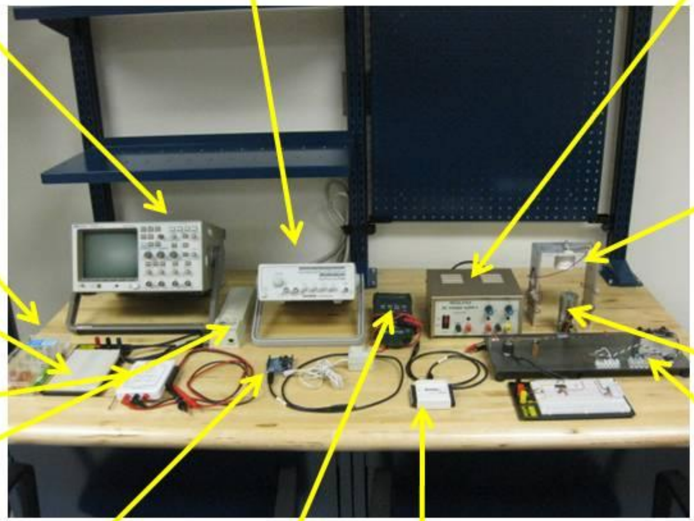
± 15 V (1 A), 5V (3 A)
DC Power Supply

Digital Oscilloscope

Assorted Wires

Magnetic
Levitation
System

Breadboard



Brushed DC Motor
with Encoder

NI
USB myDAQ

Power Strip

Arduino
Microcontroller
With Transformer
and USB Cable

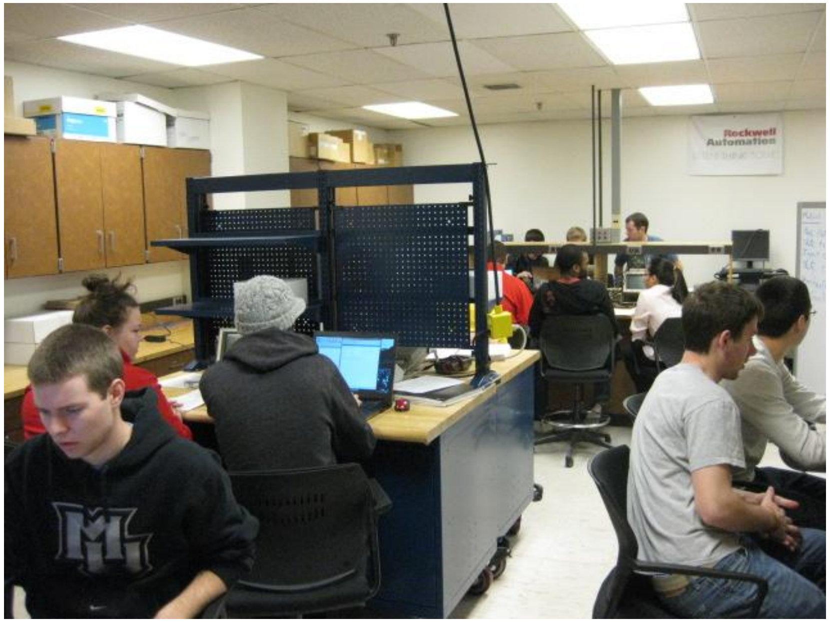
Digital Multimeter

Plus Assorted
Components:
resistors, capacitors,
inductors, op-amps,
diodes, transistors

Cantilever Beam with
Accelerometer, Strain
Gauges and Circuitry,
Solenoid
Actuator/Sensor,
Eddy-Current Damper

NI
USB 6008 DAQ

Studio Sessions



Key Concepts for Class Sessions (1st Half)

- Physical Modeling: general approach and, specifically, electrical systems (resistors, capacitors, op-amps, voltage sources, voltage meters)
- Mathematical Modeling: general approach and, specifically, electrical systems (KVL, KCL, equations for pure / ideal resistors and capacitors, op-amp golden rules, differential equation, impedance methods and use of differential operator D = d/dt)
- Analysis
  – Zero-, First-, and Second-Order Dynamic Systems: Time Response and Frequency Response
  – MatLab (step and bode commands) and Simulink Simulations of low-pass filter and feedback control system

- Control Systems
  - Open-Loop Control
  - Feedback Control
    - Stability: Strength of Corrective Action and System Dynamic Lags
    - Benefits of Negative Feedback, in particular, insensitivity to parameter variations in the plant (e.g., op-amp)
    - PID control: physical significance of each mode
    - Block Diagram System Representation and Simplification
    - Control System Design (specifically PI control) using a 2^{nd}-Order Standard-Form Transfer Function and 2^{nd}-Order-Model Performance Specifications (rise time, overshoot, and settling time)
    - Effect of an added zero to a 2^{nd}-order transfer function on the time response

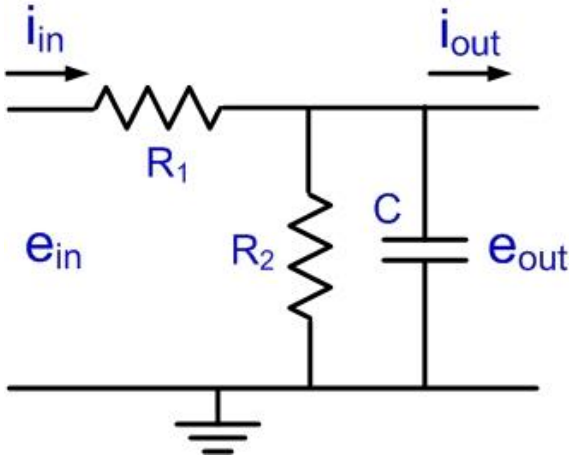
Key Concepts for Studio Sessions (1st Half)

- Basics of the Analog Function Generator, Digital Oscilloscope, Digital Multimeter, DC Power Supply, Breadboard
- Measurement of voltage, current, resistance, and capacitance; components in series and parallel; voltage-divider-circuit and low-pass-filter time and frequency response
- Use of the NI USB MyDAQ and the virtual instruments: function generator, oscilloscope, and bode plotter
- Loading of systems (circuits) by a load or measuring device: understanding input and output impedance and methods to predict and then reduce / eliminate loading
- Op-Amps: Buffer, Inverting, Non-Inverting, Difference, PI Controller, Active Low-Pass Filter
- Correspondence between circuit schematic and real system

Course Mid-Semester Case Study

- The best way to understand this course is to look at the mid-semester case study (students submit this), after 6 weeks of classes and studios, and see how we got here.
- This integrating experience is to take an existing physical system (electrical first-order system here, but it could be any physical system) and have it meet desired dynamic performance specifications.

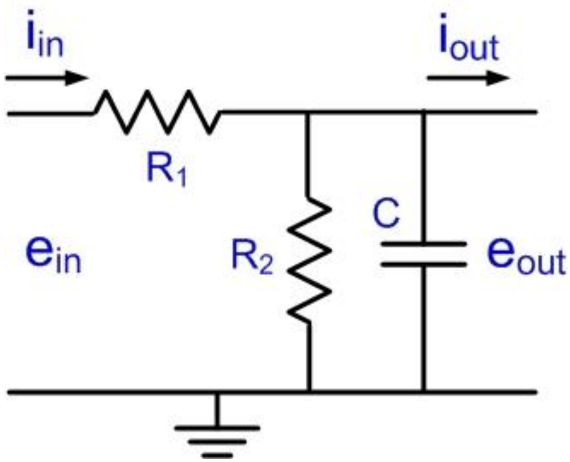
$$t_{r_{10\%-90\%}} \le 0.015 \text{ sec}$$
$$M_p \le 25\%$$
$$t_{s_{1\%}} \le 0.09 \text{ sec}$$
$$\text{Control Effort} \le 13 \text{ V}$$
$$\text{SS Error} = 0$$



Electrical Physical System

Process

– Can the system alone (i.e., open loop) meet the performance specifications, i.e., unit step response with desired rise time, overshoot, and settling time?



$$R1 = 100\ K\Omega$$
$$R2 = 100\ K\Omega$$
$$C = 1\ \mu F$$

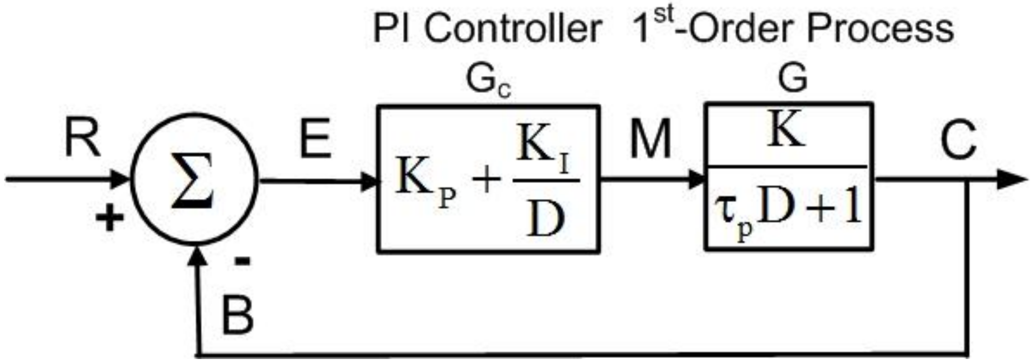
Physical System

- Make simplifying assumptions (e.g., pure and ideal resistors and capacitor, no loading) and create the **physical model**.
- Apply KVL and KCL, along with component constitutive equations, to obtain the **mathematical model**.

$$\frac{e_o}{e_i} = \frac{\dfrac{R_2}{R_1+R_2}}{\dfrac{R_1R_2}{R_1+R_2}CD+1} = \boxed{\frac{K}{\tau_p D+1}} = \frac{0.5}{0.05D+1}$$

1st-Order

- **Analysis** (use hand calculation or MatLab analysis) shows that the system time constant is too large and operating open-loop cannot meet the performance specifications. What to do?
- Change the physical system! Here we assume that the physical system cannot be changed.
- Apply closed-loop (feedback) control to obtain the desired response and use the PI (proportional-integral) controller.



90% of the controllers used in the world are PI Controllers!

$$\frac{C}{R} = \frac{G_c G}{1 + G_c G} = \frac{\dfrac{KK_I}{\tau_p}\left(\dfrac{K_P}{K_I} D + 1\right)}{D^2 + \dfrac{KK_P + 1}{\tau_p} D + \dfrac{KK_I}{\tau_p}} = \frac{\omega_n^2 \left(\tau D + 1\right)}{D^2 + 2\zeta\omega_n D + \omega_n^2}$$

– Comparison of the actual transfer function with the standard-form transfer function gives the following relationships:

$$\tau = \frac{K_p}{K_i} \qquad \omega_n^2 = \frac{KK_i}{\tau_p} \qquad \zeta = \frac{1+K_pK}{2\sqrt{\tau_p K_i K}}$$

– We now have relationships between the control gains, K_p and K_i, and the dynamic performance indictors for a pure second-order dynamic system, ω_n and ζ.

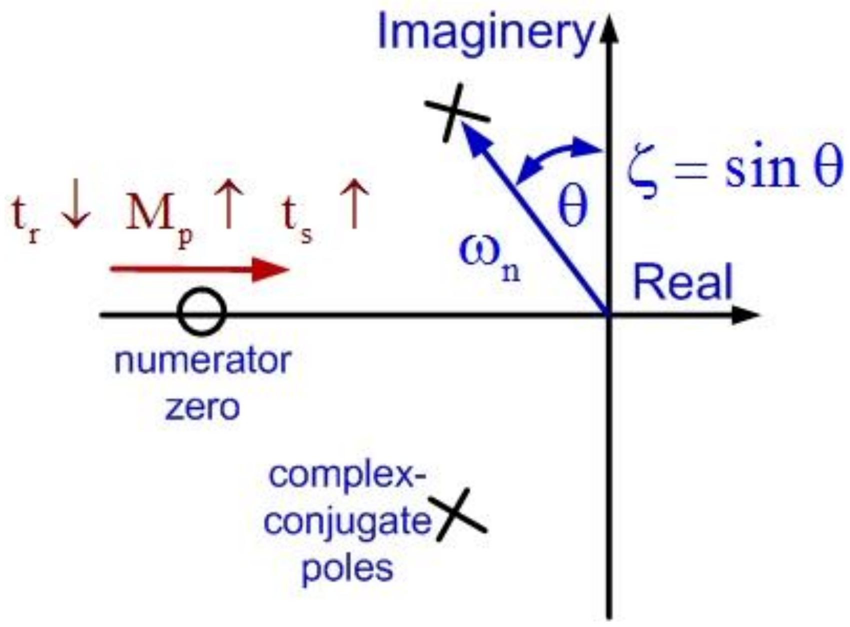
$$K_i = \frac{\tau_p \omega_n^2}{K} \qquad Kp = \frac{1}{K}\left[2\zeta\sqrt{\tau_p K_i K} - 1\right]$$

$$t_{r_{10\%-90\%}} \approx \frac{1.8}{\omega_n} \qquad M_p = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}} \qquad t_{s_{1\%}} \approx \frac{4.6}{\zeta\omega_n}$$

– But Wait! This is not a pure 2nd-order dynamic system. There are numerator dynamics – the numerator has a 1st-order term! Not to worry – why?

– We know that for a pure 2nd-order dynamic system, with the damping ratio ζ between 0 and 1 (typical of most operating engineering systems), the roots of the differential-equation characteristic equation are complex conjugates (indicated by an **x**).

The numerator dynamics, i.e., the 1st-order term, has a root $-1/\tau$ called a zero, indicated with a **o**. As the zero moves along the real axis closer to the pole locations, system dynamic behavior is affected as shown. <u>Take this effect into account in the design!</u>



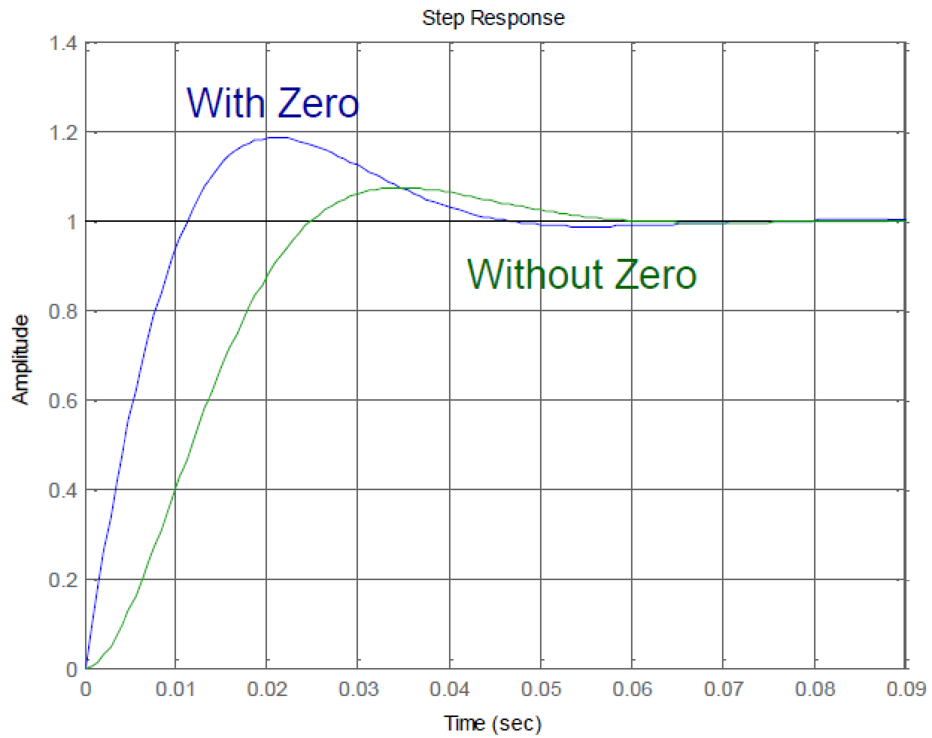
– Choose $\omega_n = 118$ and $\zeta = 0.64 \;\rightarrow\; K_i = 1392$ and $K_p = 13.1$
– The predicted performance values for a pure 2nd-order system are:

$$t_{r_{10\%-90\%}} \approx \frac{1.8}{\omega_n} = 0.015 \qquad M_p = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}} = .073 \qquad t_{s_{1\%}} \approx \frac{4.6}{\zeta\omega_n} = .061$$

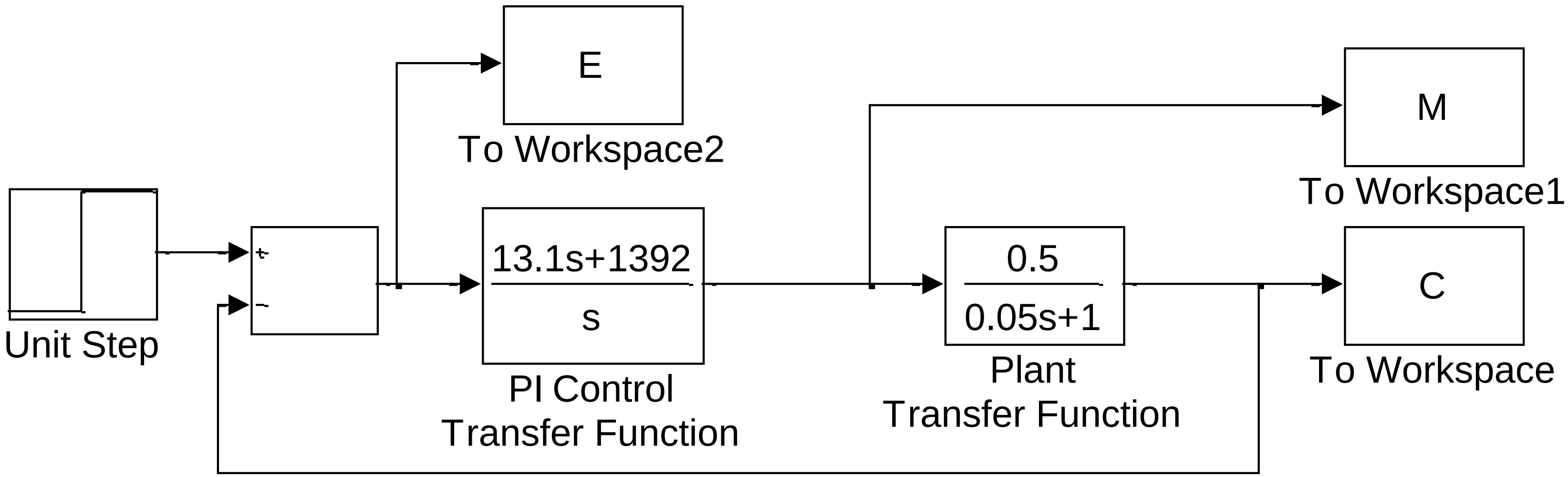
Note the effect of the zero:
$t_r \downarrow$, $M_p \uparrow$, and $t_s \uparrow$

pole locations: -75.5 ± 90.7i
zero location: -106.3

<u>System Performance</u>
$t_r = .0086$ $M_p = .185$ $t_s = .063$



– Our design meets the performance specifications. But what about the control effort? We are going to first implement our design with analog op-amps and we know that the maximum output of an op-amp is about 13 volts when powered by ± 15 V. We use Simulink to check the control effort.

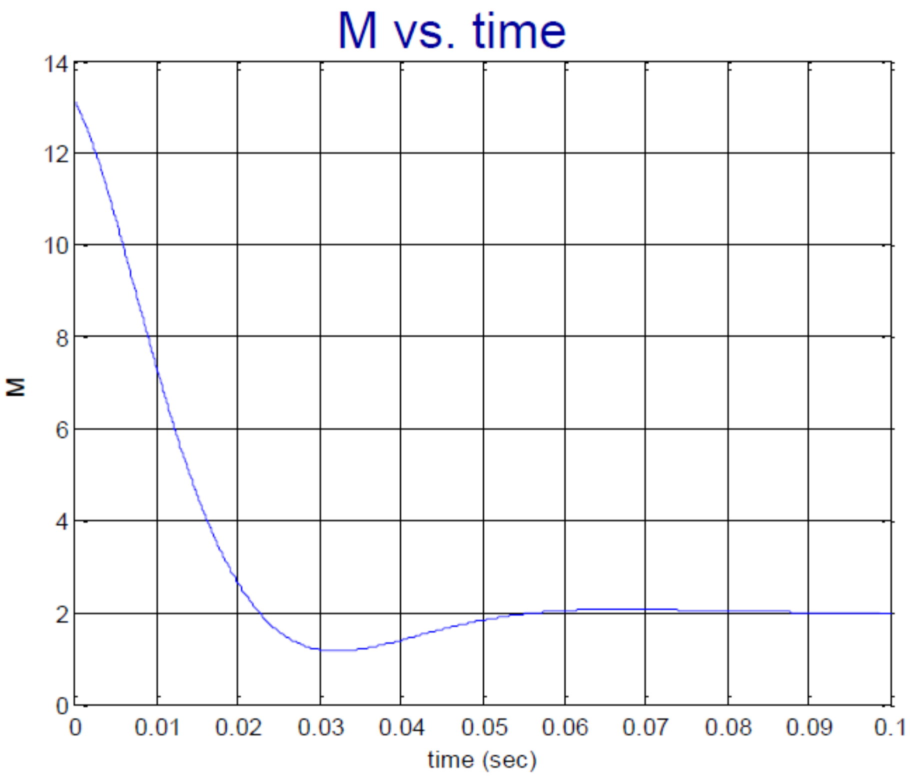


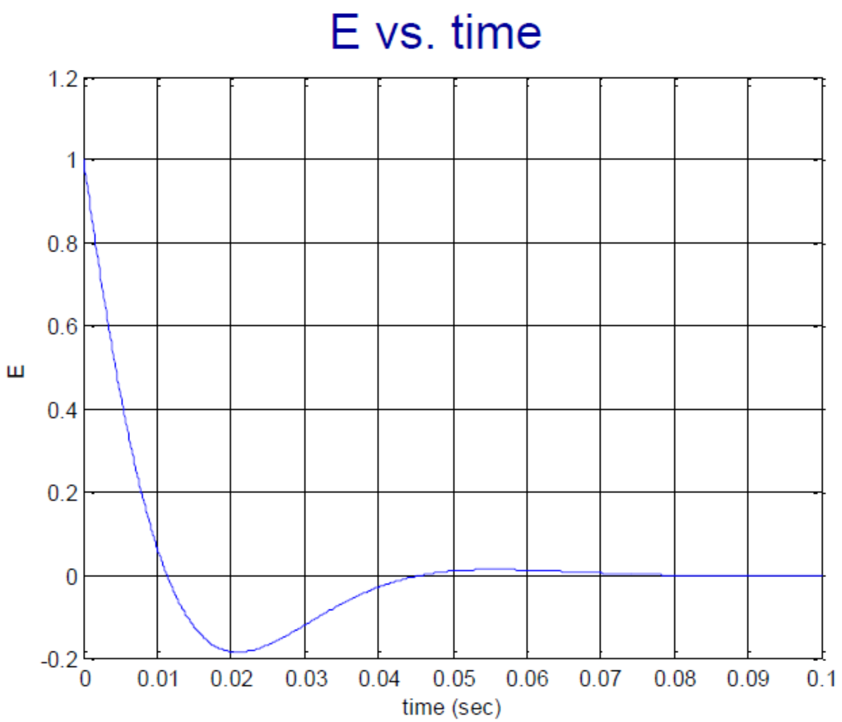
PI Control of a First-Order Plant

MatLab Simulink Block Diagram

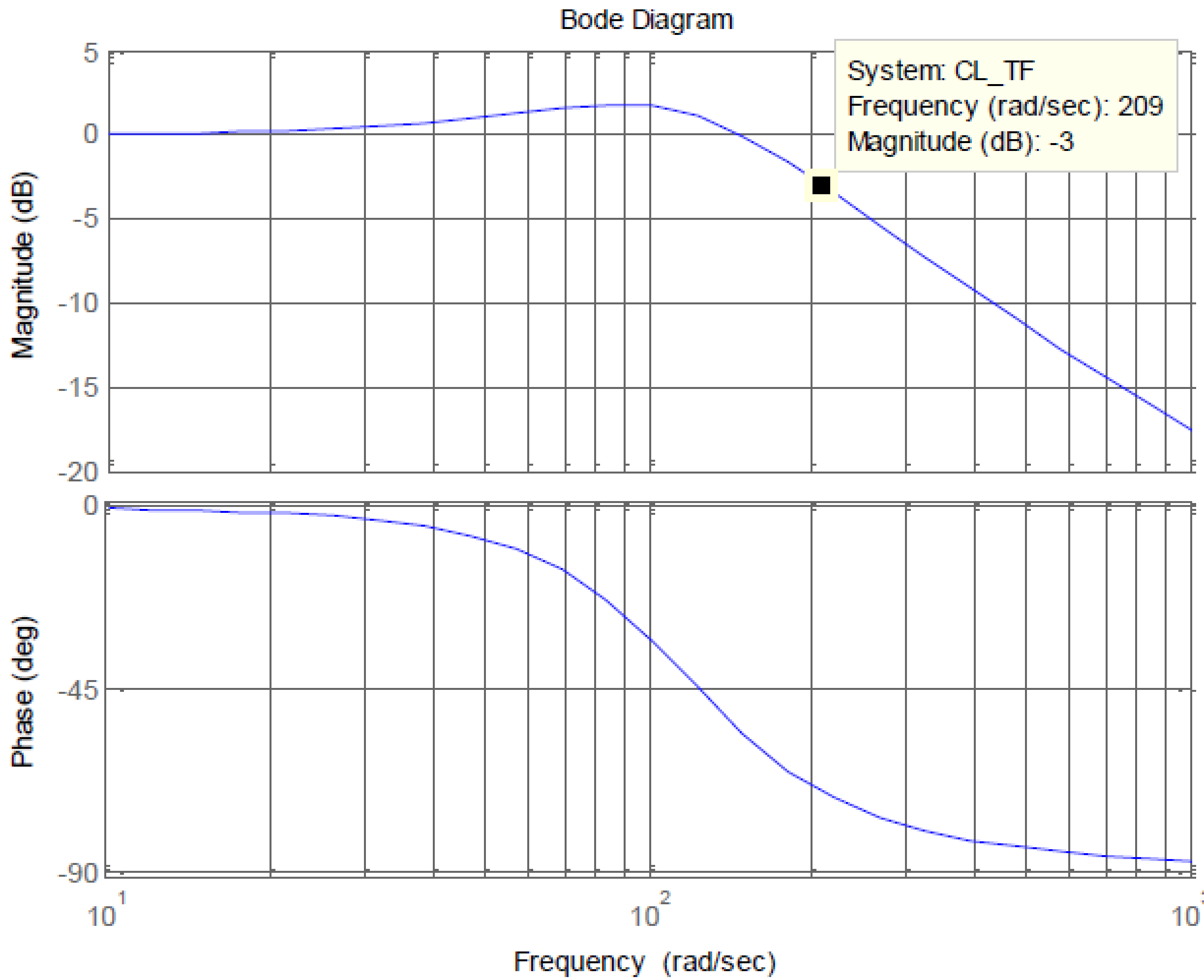
Control Effort

M < 13 volts





Error Signal



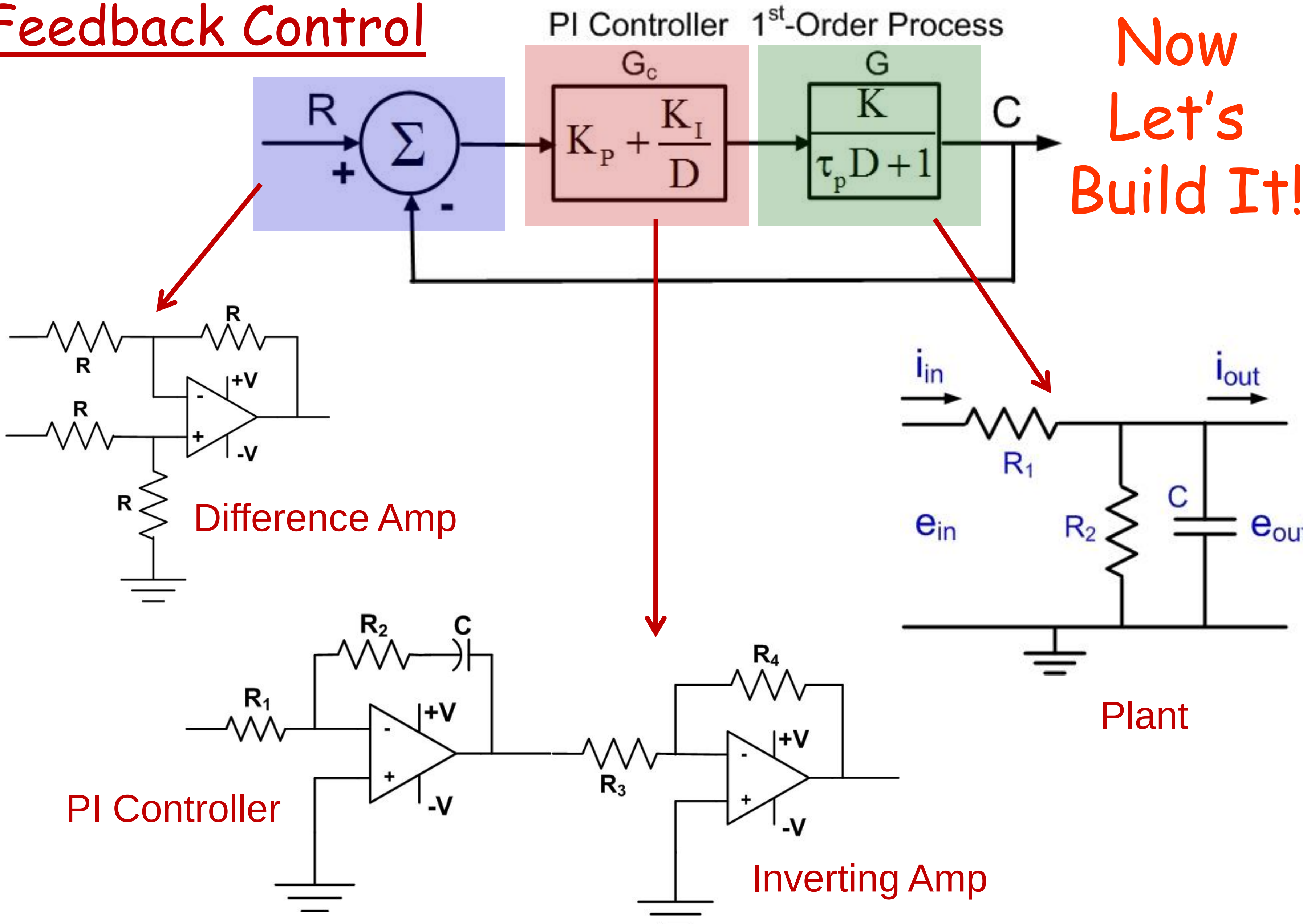
Bandwidth
33.3 Hz

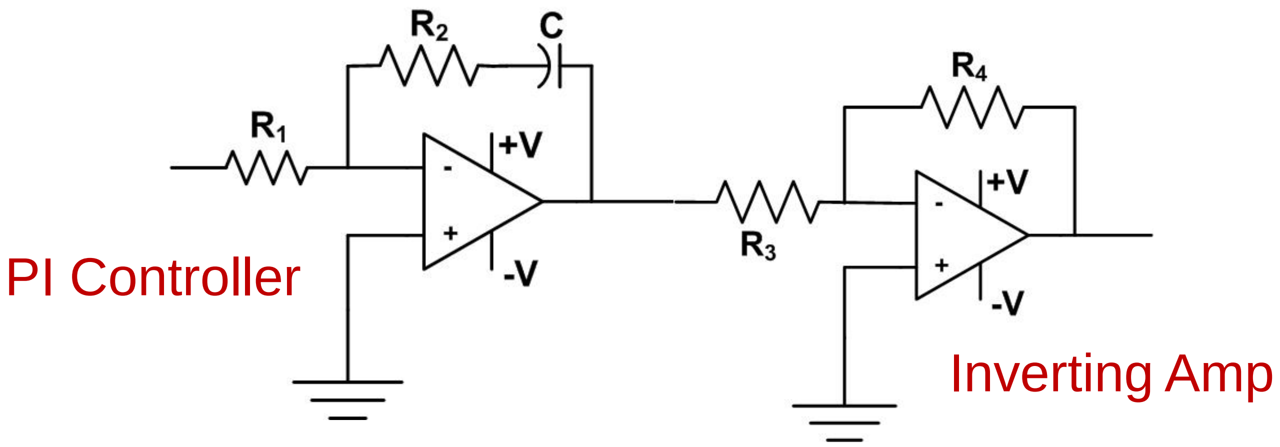
Analytical Closed-Loop Bode Plot

Note: Frequency Response will be studied and used more extensively in the 2nd half of the course.

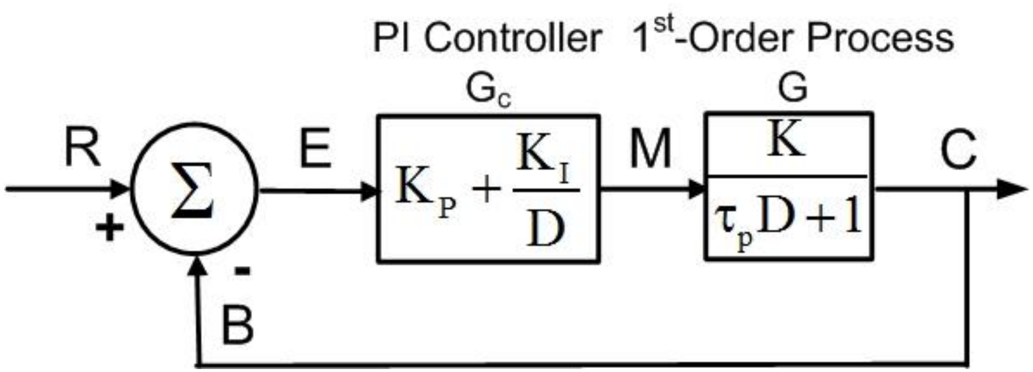
Feedback Control

Now Let's Build It!





$$\frac{e_o}{e_i} = \frac{-\left(R_2 + \frac{1}{C_D}\right)}{R_1}\left(-\frac{R_4}{R_3}\right) = \left(\frac{R_4}{R_3R_1C}\right)\left(\frac{R_2CD+1}{D}\right)$$



$$\frac{M}{E} = K_p + \frac{K_i}{D} = K_i\left(\frac{\frac{K_p}{K_i}D+1}{D}\right)$$

$$\boxed{K_i = \frac{R_4}{R_3R_1C} \qquad Kp = \frac{R_2R_4}{R_3R_1}}$$

$R1 = 1K\Omega$ $\quad R3 = 1.3K\Omega$ $\quad C = 1.0\mu F$

$R2 = 9.1K\Omega$ $\quad R4 = 1.8K\Omega$

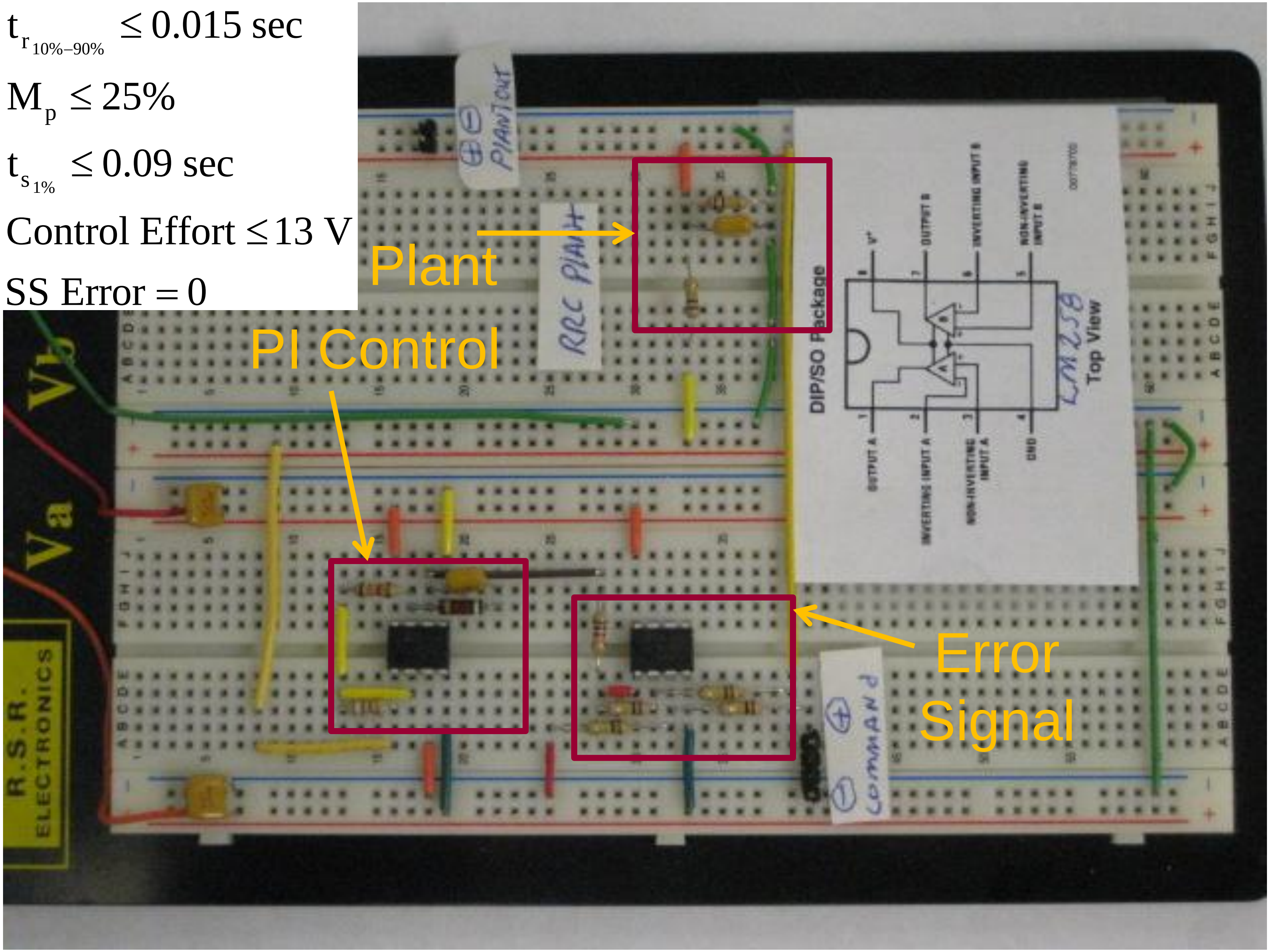
$t_{r_{10\%-90\%}} \le 0.015$ sec

$M_p \le 25\%$

$t_{s_{1\%}} \le 0.09$ sec

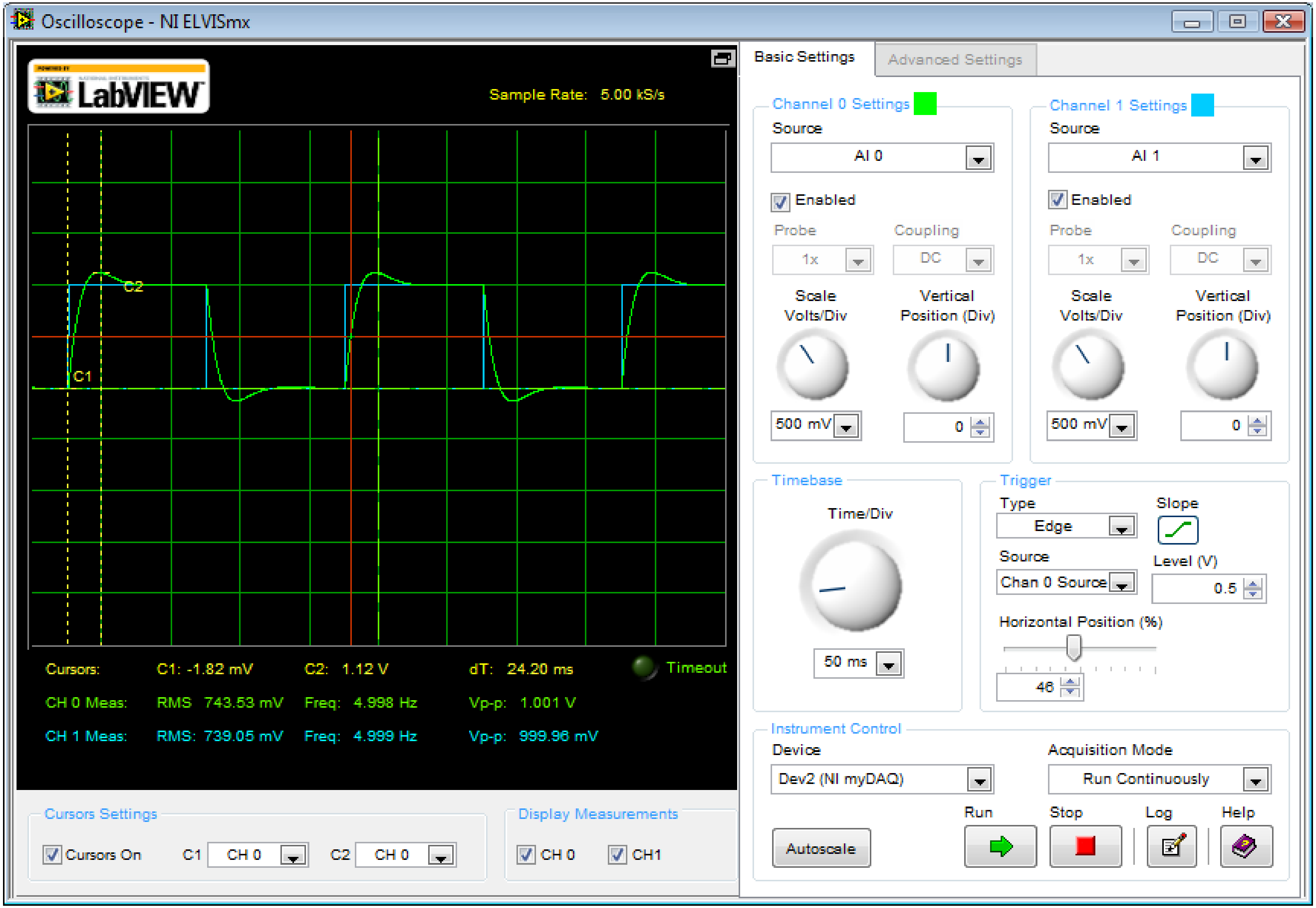
Control Effort ≤ 13 V

SS Error $= 0$

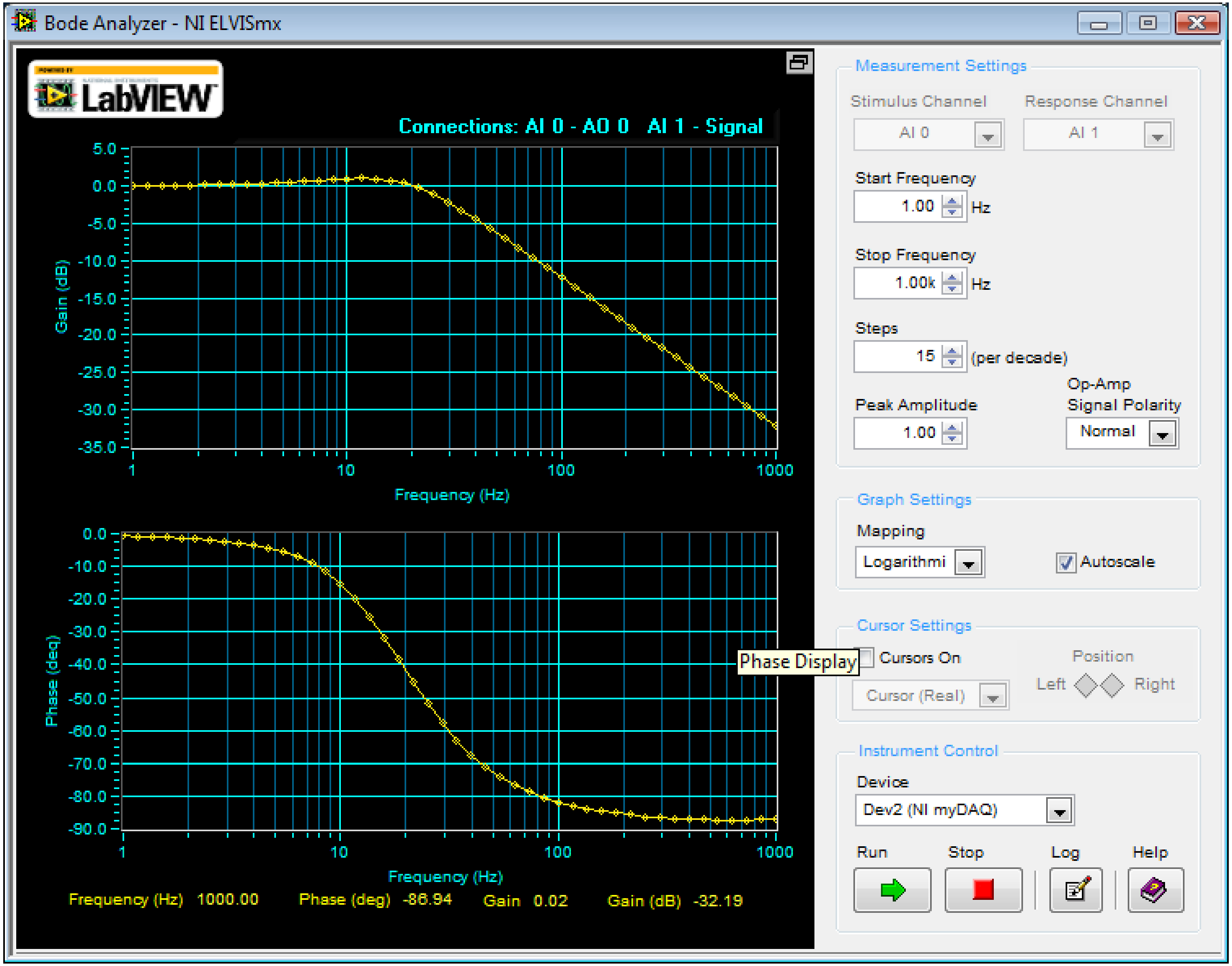


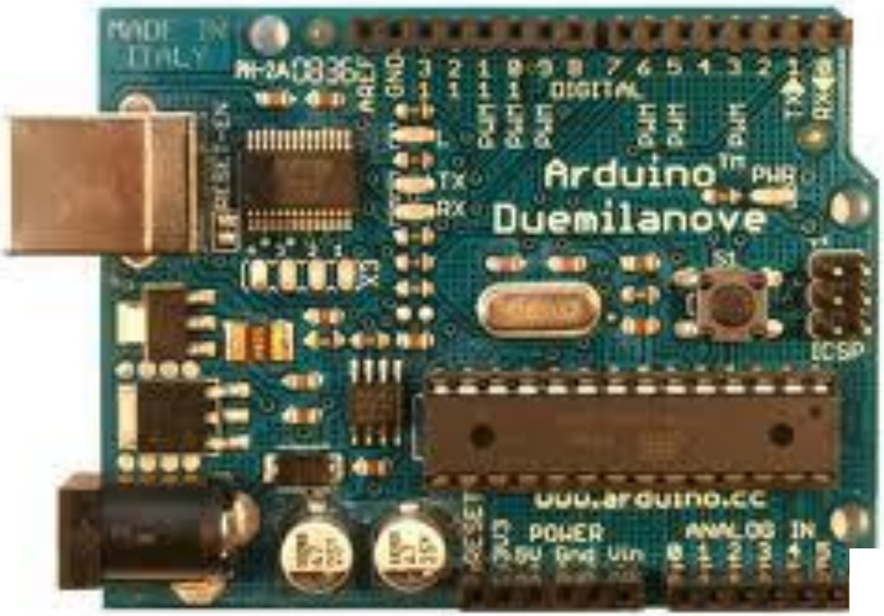
PI Analog Control of a 1st-Order Plant

Measurement: Closed-Loop Step-Response Plot – NI MyDAQ



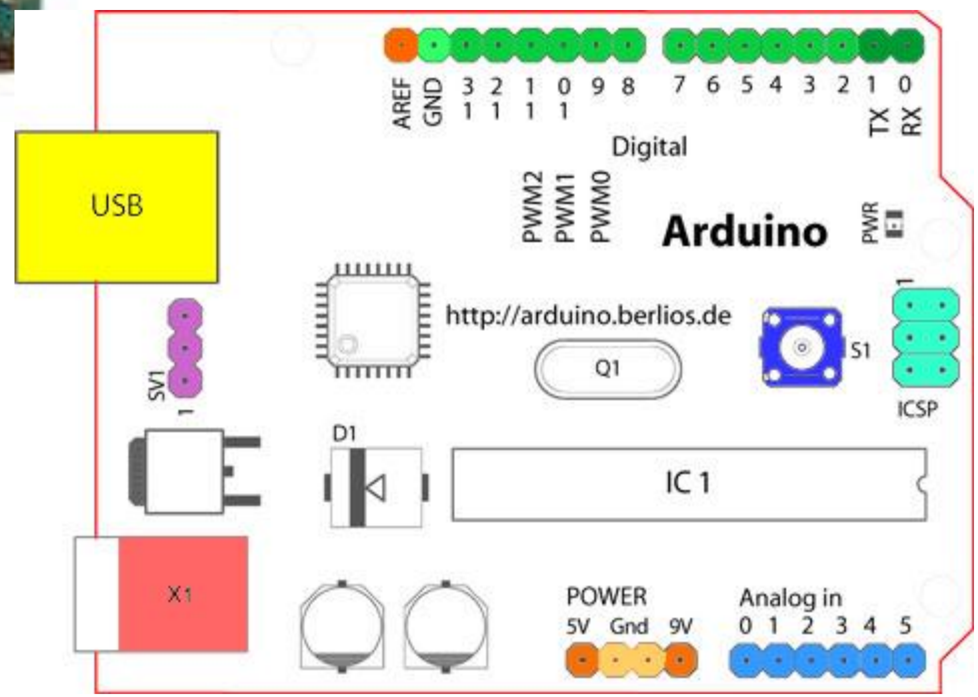
Measurement: Closed-Loop Bode Plot – NI MyDAQ





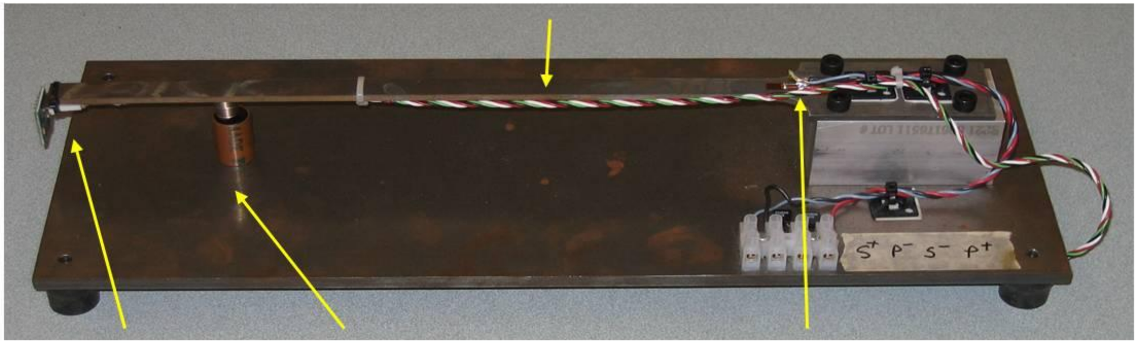
What's Next In the 2nd Half ?

Microprocessor PWM PI Control of a 1st-Order Plant with the MatLab / Simulink Real-Time Workshop



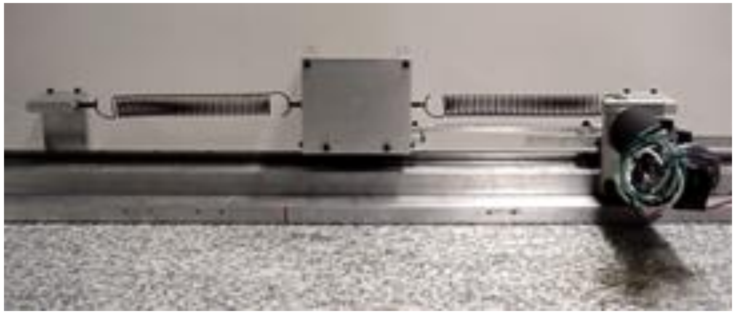
Two-Mass, Three-Spring System

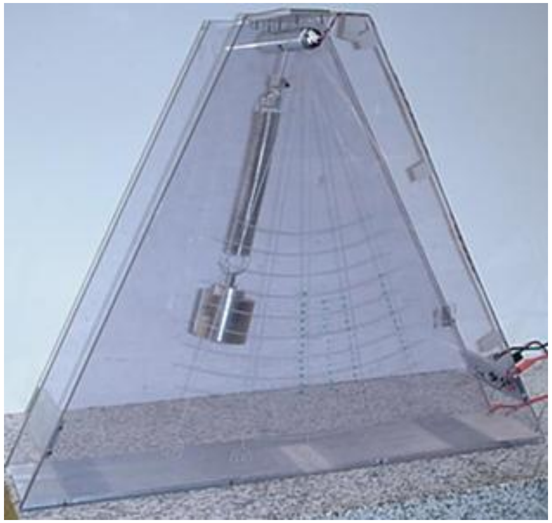
Steel Cantilever Beam



Accelerometer Eddy-Current Damper Strain Gage

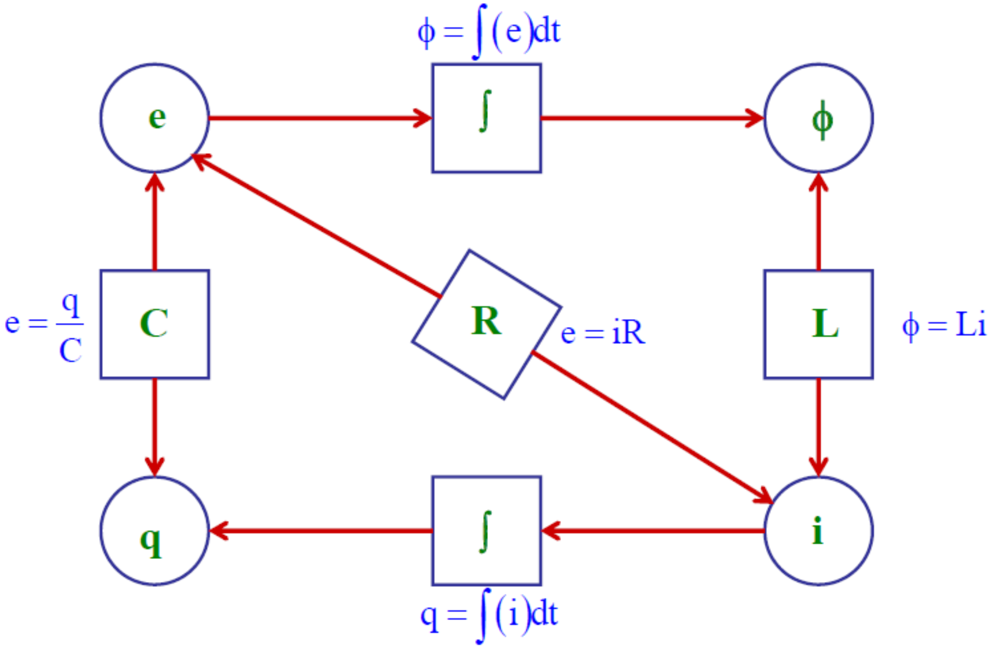
Spring-Mass-Damper Systems

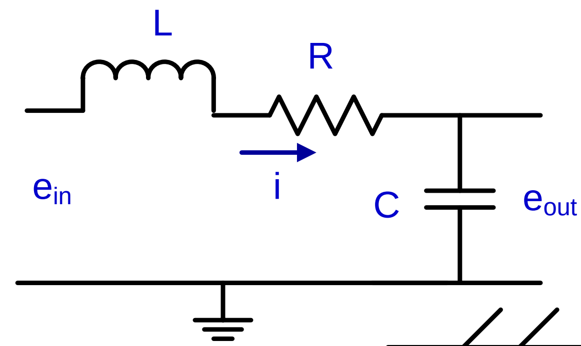


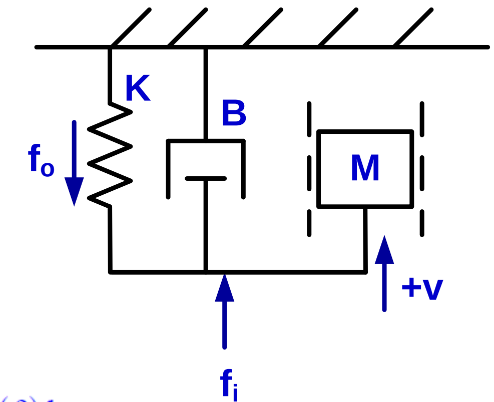


Spring Pendulum

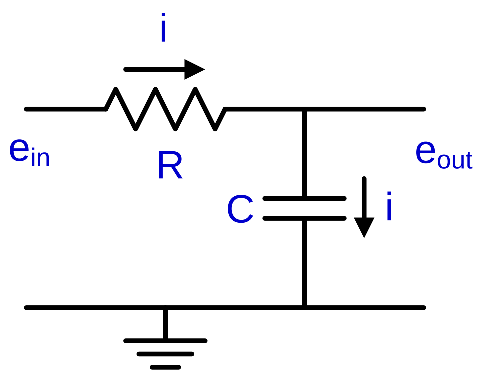
Mechanical Systems

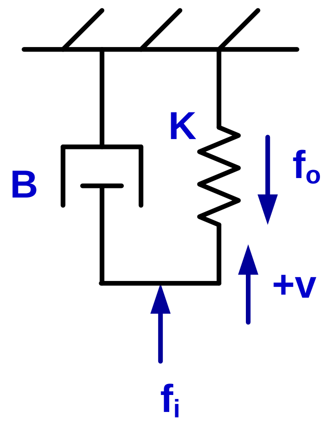


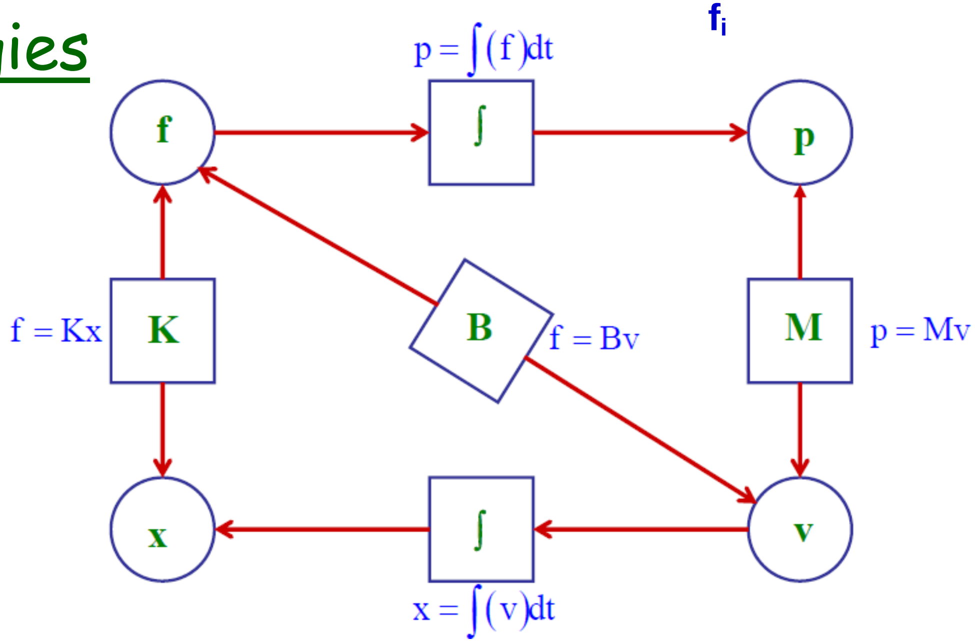




Electrical-Mechanical Analogies





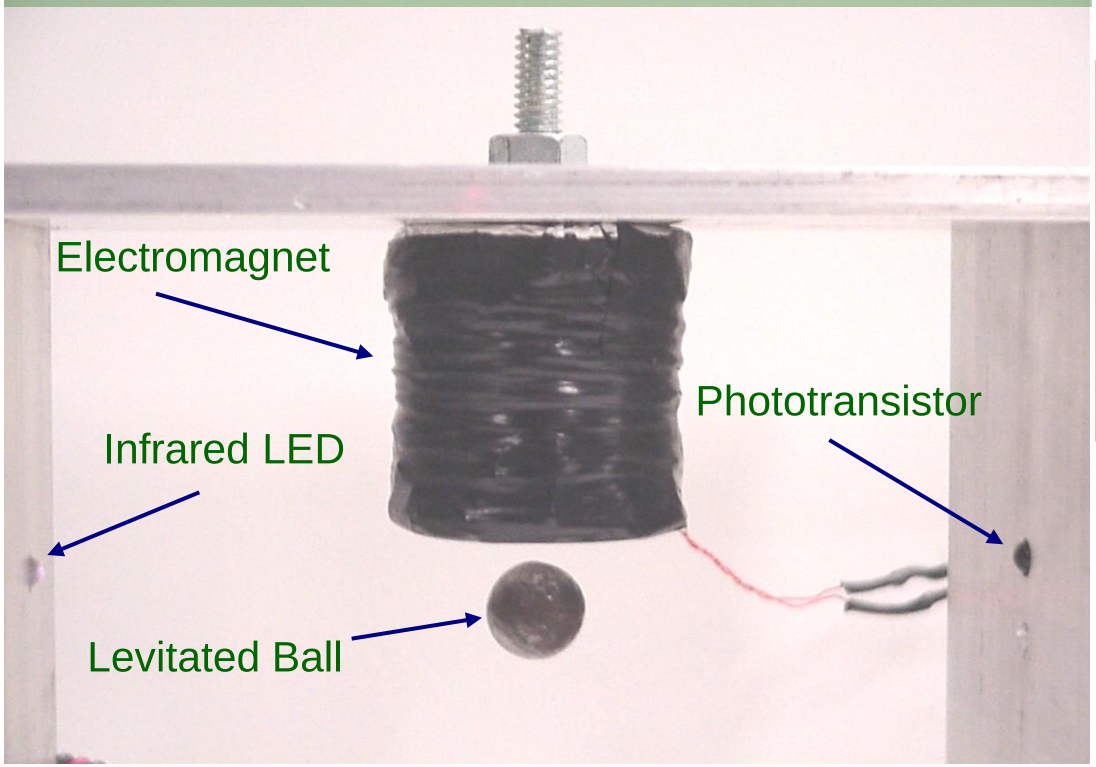


Electromechanical Systems

(6 stations for each system)

Pittman 8322S001

Magnetic Levitation System



Brushed DC Motor with Optical Encoder: Speed Control

Analog & Microcontroller Control Implementation