Mechatronics

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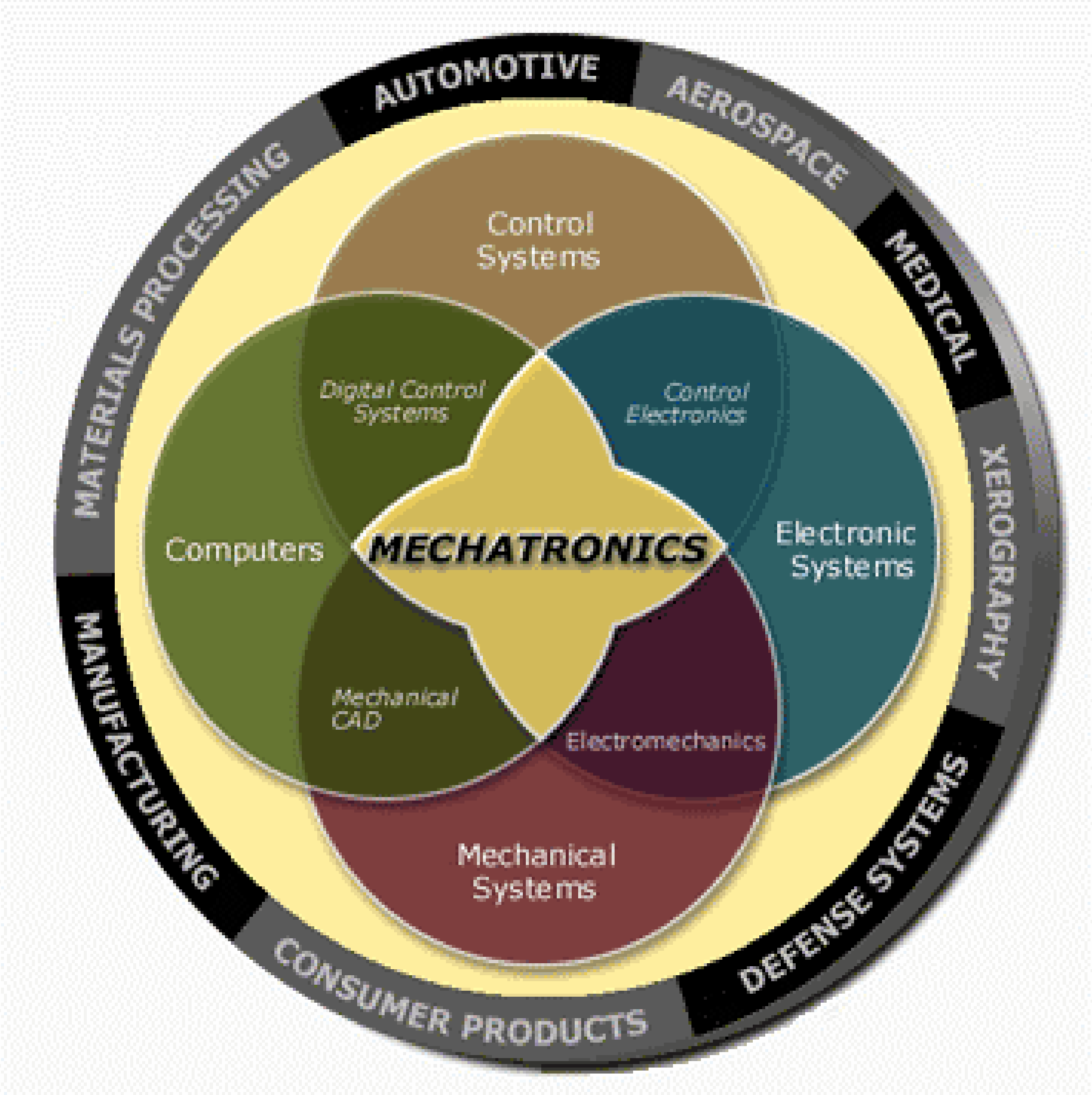
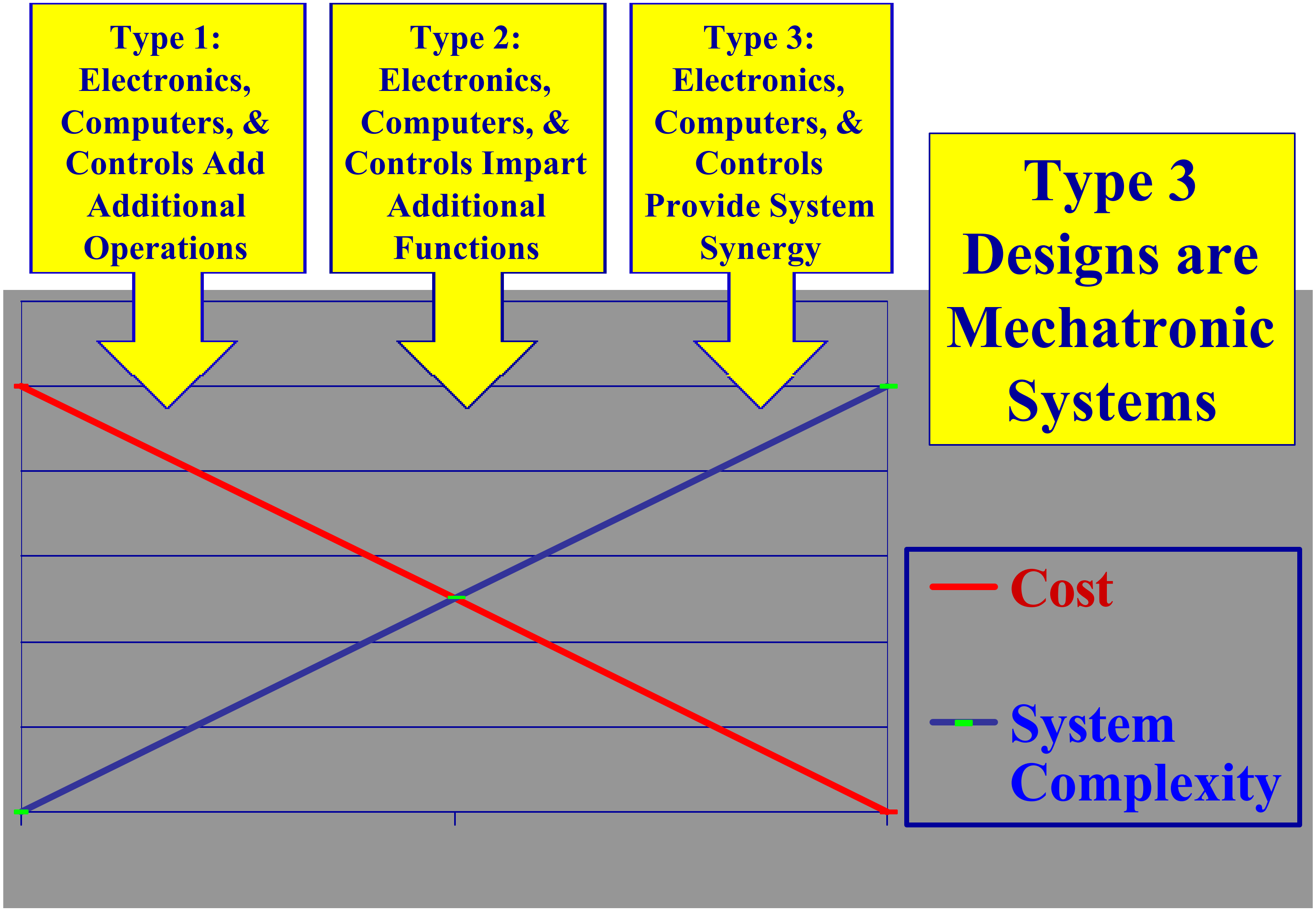
What is Mechatronics?

Mechatronics is the ***synergistic*** combination of mechanical engineering, electronics, controls engineering, and computers, all ***integrated*** through the design process.



Electro-Mechanical Designs



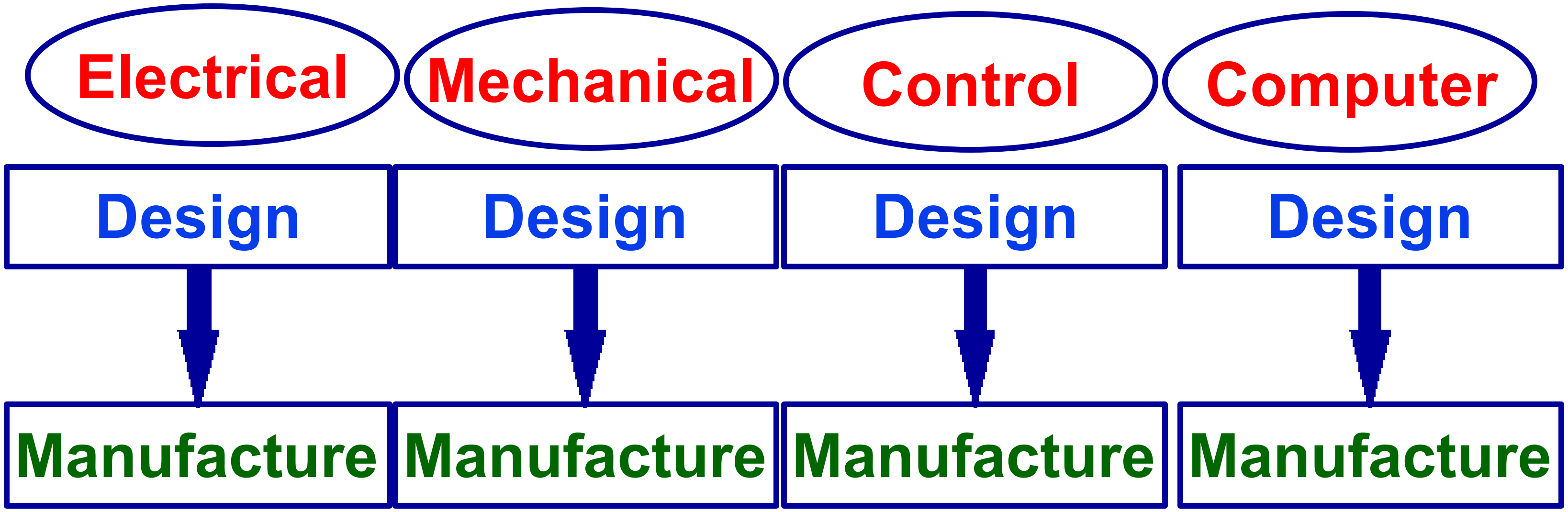
Type 1: Electronics, Computers, & Controls Add Additional Operations

Type 2: Electronics, Computers, & Controls Impart Additional Functions

Type 3: Electronics, Computers, & Controls Provide System Synergy

Type 3 Designs are Mechatronic Systems

“Over the Wall” State



Electrical

Mechanical

Control

Computer

Design → Manufacture

Design → Manufacture

Design → Manufacture

Design → Manufacture

Concurrent Engineering

Electrical	Mechanical	Control	Computer
Design + Manufacture	Design + Manufacture	Design + Manufacture	Design + Manufacture

Mechatronics

Electrical **Mechanical** **Control** **Computer**

Design

+

Manufacture

The Design Challenge

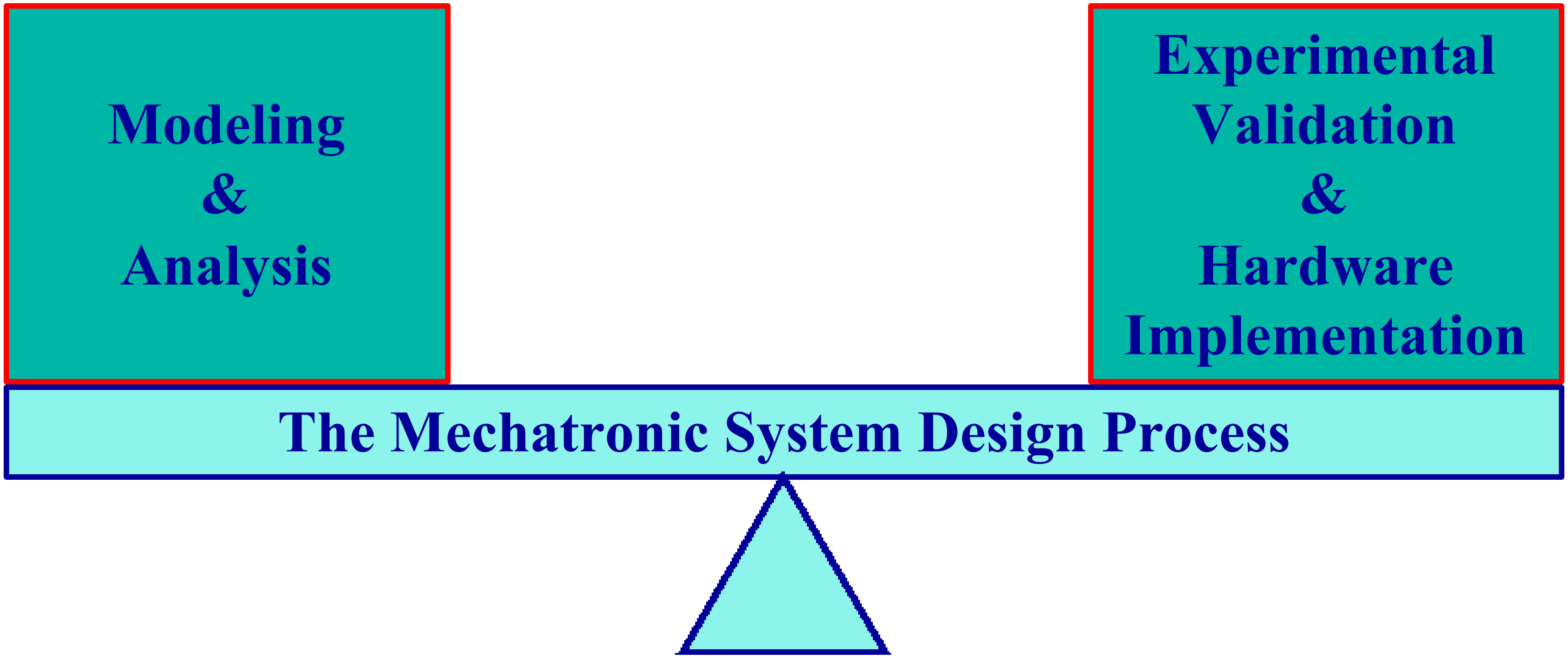
The cost-effective incorporation of electronics, computers, and control elements in mechanical systems requires a new approach to design.

The modern engineer must draw on the synergy of ***Mechatronics*****.**

Difficulties in Mechatronic Design

- Requires ***System*** Perspective
- ***System*** Interactions Are Important
- Requires ***System*** Modeling
- Control ***Systems*** Go Unstable

Balance: The Key to Success



Modeling & Analysis

Experimental Validation & Hardware Implementation

The Mechatronic System Design Process

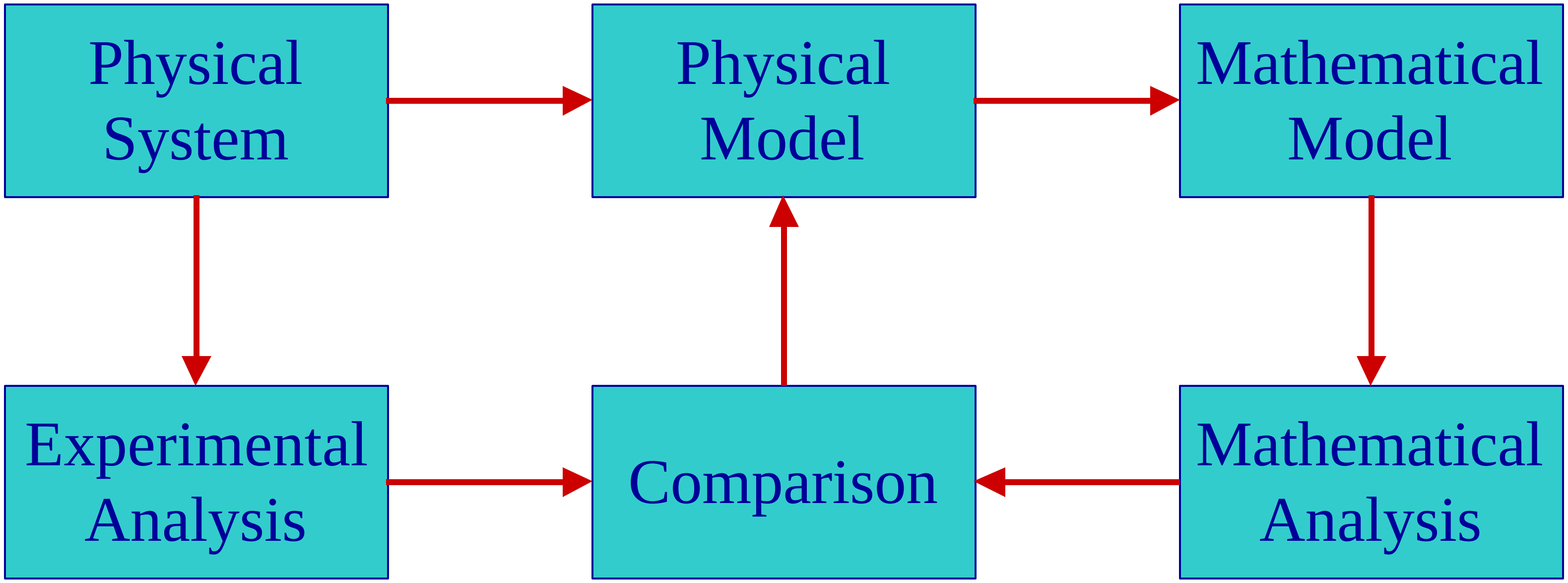
Computer Simulation Without Experimental Verification Is At Best Questionable, And At Worst Useless!

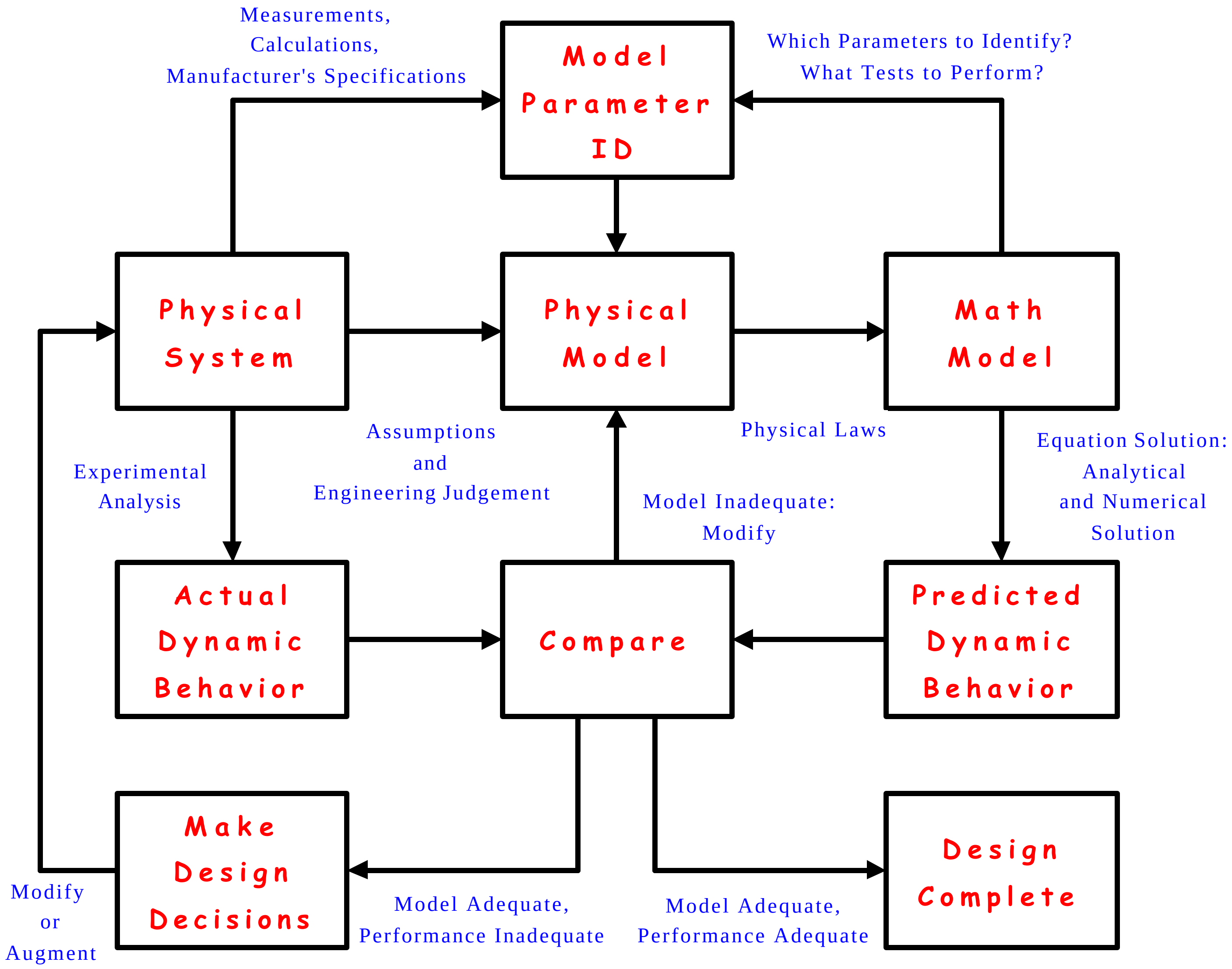
Balance in Mechatronics is the Key!

The essential characteristic of a mechatronics engineer and the key to success in mechatronics is a *balance* between the following sets of skills:

- modeling (physical and mathematical), analysis (closed-form and numerical simulation), and control design (analog and digital) of dynamic physical systems
- experimental validation of models and analysis (*for computer simulation without experimental verification is at best questionable, and at worst useless!*) and understanding the key issues in hardware implementation of designs

Dynamic System Investigation





Dynamic System Investigation

Mechatronics is NOT Concurrent Engineering

CONCURRENT ENGINEERING

Bridges Design and Manufacturing.
Electrical, Mechanical, Control and Computer Engineers
Operate in Separate Environments.
(vertical integration)

MECHATRONICS

Integration of Electrical, Mechanical, Control, and Computer Engineering Knowledge
in Both Design and Manufacturing.
(horizontal & vertical integration)

Mechatronics is NOT Electromechanics

ELECTROMECHANICS

Design of prime movers: a.c. motors, d.c. motors, solenoids. Design of generators. Control of motors: commutation of d.c. motors, startup of a.c. motors.

MECHATRONICS

The synergistic combination of actuators, sensors, control systems, and computers in the design process.

Mechatronics is MORE than just Control Systems

Mechatronics draws heavily on the concepts of control systems only because they provide a coherent framework for system analysis.

Controls are an integral component to any mechatronic design and not an afterthought add-on.

However, open-loop and feedforward control structures are as valid as feedback ones for design solutions.

Benefits of Mechatronics

Mechatronics is spawning a new breed of intelligent components and systems that combine an optimum blend of all available technologies.

- Shorter Development Cycles
- Lower Costs
- Increased Quality
- Increased Reliability
- Increased Performance
- Increased Benefits to Customers

The Realm of Mechatronics

- High Speed
- High Precision
- High Efficiency
- Highly Robust
- Micro-Miniature

Mechatronic Design Concepts

- Direct Drive Mechanisms
- Simple Mechanics
- System Complexity
- Accuracy and Speed from Controls
- Efficiency and Reliability from Electronics
- Functionality from Microcomputers

Think System !

Mechatronics Engineer

- Leader in the initiation and integration of design
- Interdisciplinary knowledge of various techniques
- Ability to master the entire design process from concept to manufacturing
- Ability to use the knowledge resources of other people and the particular blend of technologies which provide the most optimal design solution

Mechatronic Areas of Study

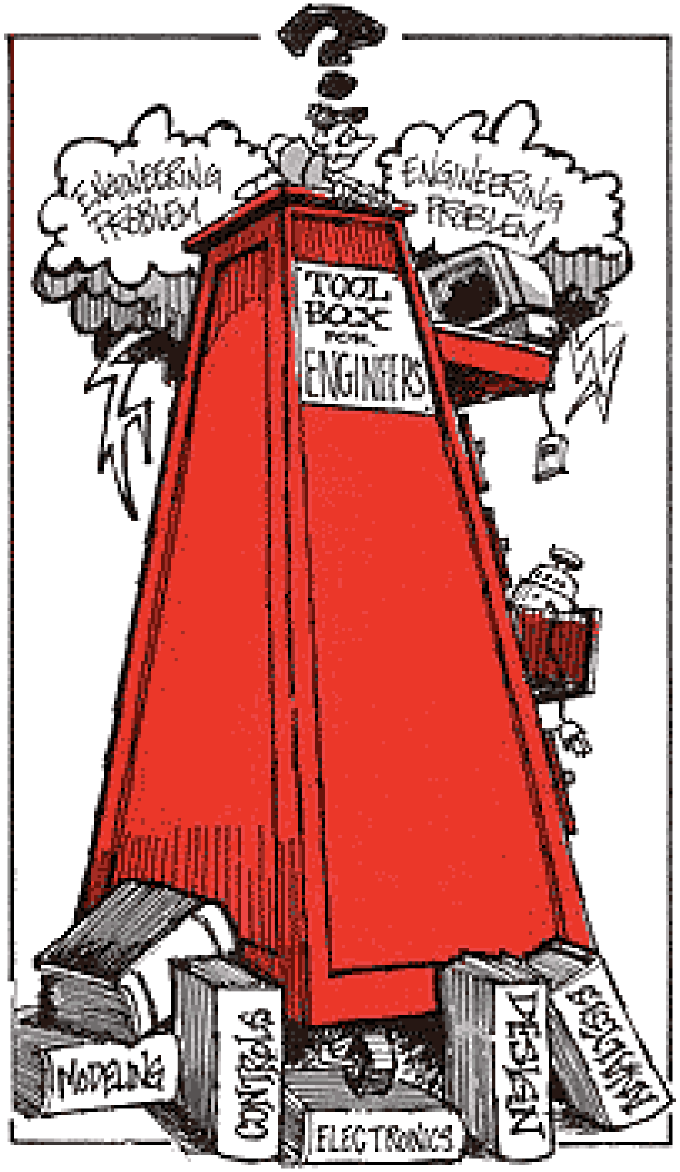
- Mechatronic system design principles
- Modeling, analysis, and control (continuous and discrete) of dynamic physical systems
- Analog and digital control electronics
- Control sensors and actuators
- Interfacing sensors, actuators, and microcontrollers
- Real-time programming for control
- Advanced topics, e.g.,
    - fuzzy logic control
    - smart materials as sensors and actuators
    - magnetic bearings

Challenge to Industry

- Control Design and Implementation is still the domain of the specialist.
- Controls and Electronics are still viewed as afterthought add-ons.
- Electronics and Computers are considered costly additions to mechanical designs.
- Few engineers perform any kind of modeling.
- Mathematics is a subject not viewed as enhancing one’s engineering skills but as an obstacle to avoid.
- Few engineers can balance the modeling\analysis and hardware implementation essential for Mechatronics.

Industry's Choices

- Train the engineers you have in the mechatronics approach to design.
- Give them the tools to be successful:
  - Knowledge: modeling, analysis, controls
  - Hardware: sensors, actuators, instrumentation, real-time control, microcontrollers
  - Software for Simulation and Control Design, e.g., Matlab / Simulink, Electronics Workbench
- Give them the time to use these tools!



OR

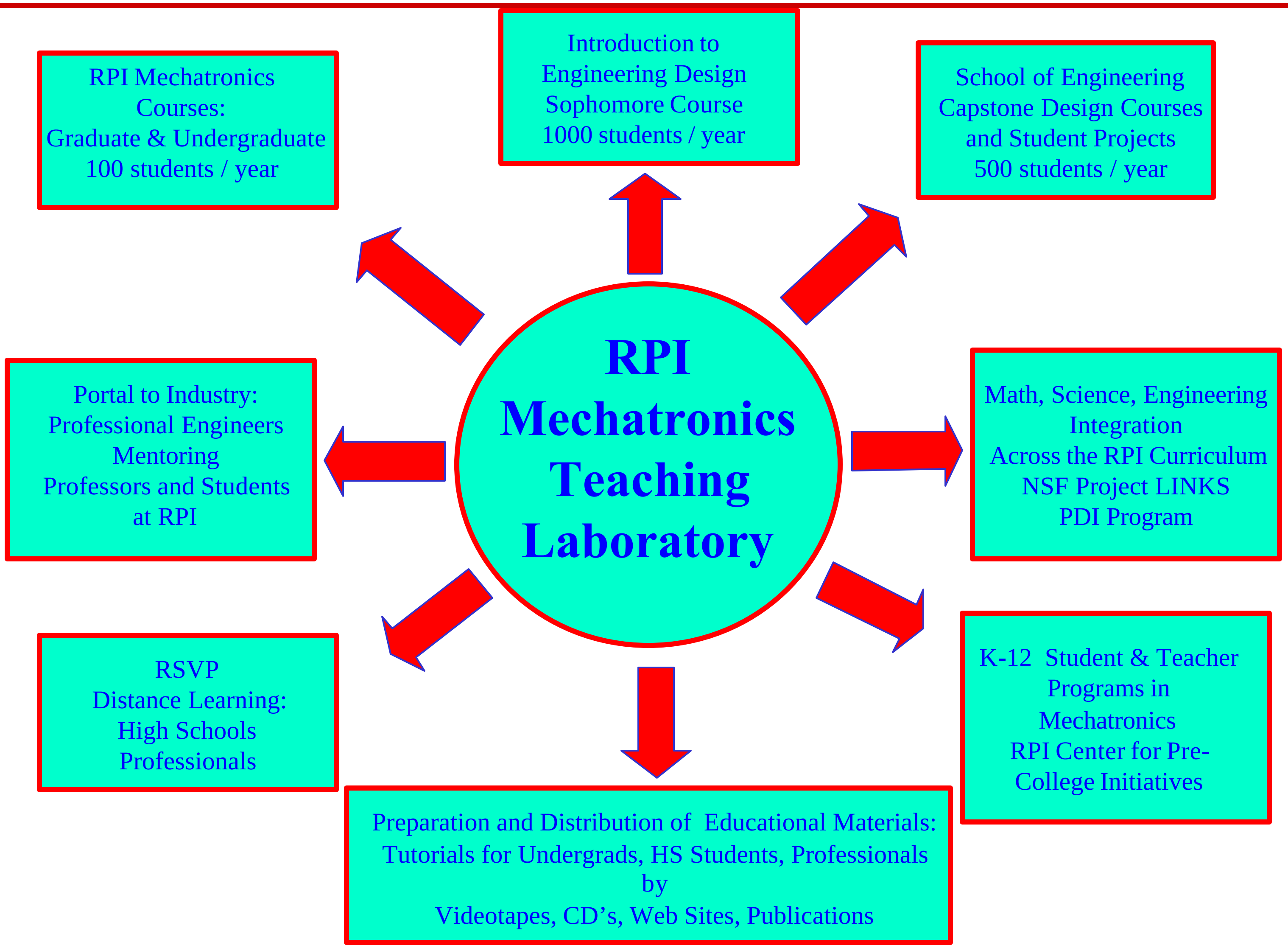
Have this happen to your engineers!

Industry's Bottom Line

Train your engineers in a Mechatronics approach to design.

Give them the tools and the time to design with synergy and integration.

Mechatronics at RPI



RPI
Mechatronics
Teaching
Laboratory

Introduction to
Engineering Design
Sophomore Course
1000 students / year

School of Engineering
Capstone Design Courses
and Student Projects
500 students / year

Math, Science, Engineering
Integration
Across the RPI Curriculum
NSF Project LINKS
PDI Program

K-12 Student & Teacher
Programs in
Mechatronics
RPI Center for Pre-College Initiatives

Preparation and Distribution of Educational Materials:
Tutorials for Undergrads, HS Students, Professionals
by
Videotapes, CD's, Web Sites, Publications

RSVP
Distance Learning:
High Schools
Professionals

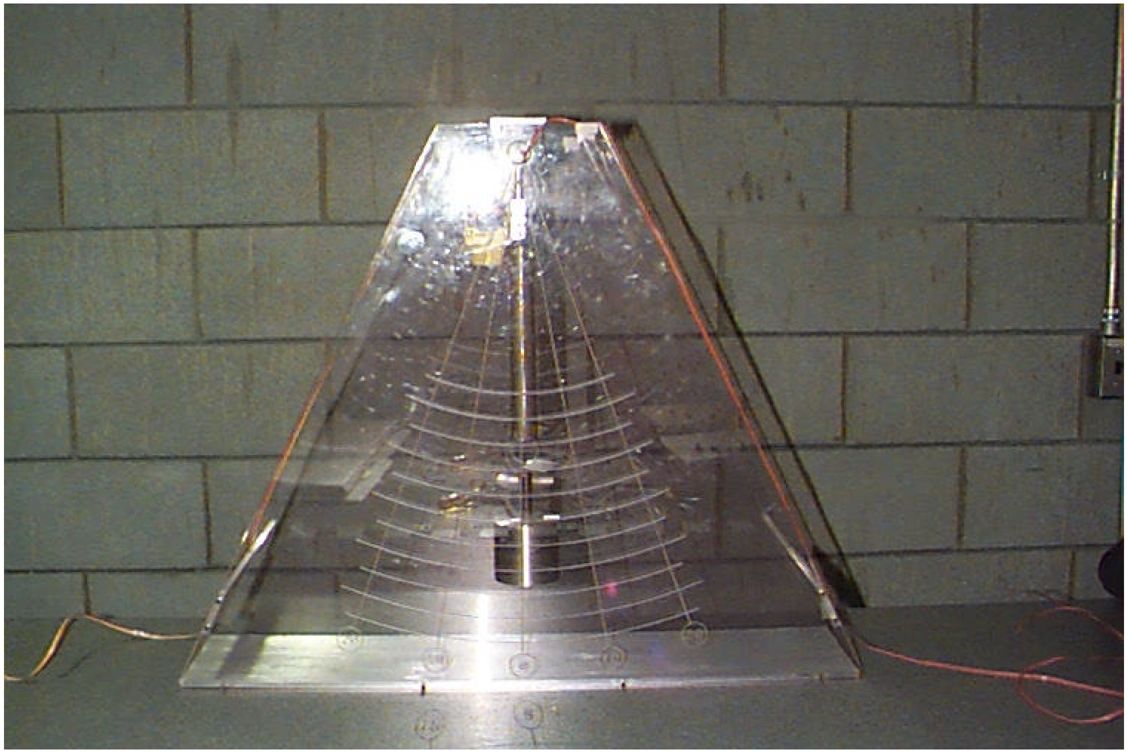
Portal to Industry:
Professional Engineers
Mentoring
Professors and Students
at RPI

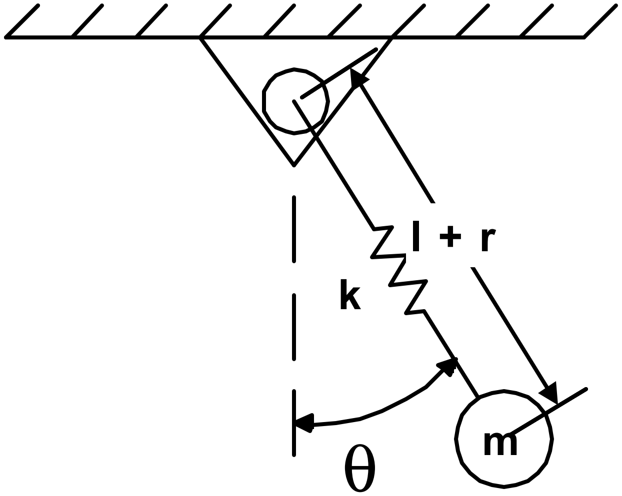
RPI Mechatronics
Courses:
Graduate & Undergraduate
100 students / year

Mechatronics Demonstrations

- Spring-Pendulum Dynamic System
- Inverted-Pendulum Dynamic System: Rotary and Arm-Driven
- Two-Mass, Three-Spring Dynamic System
- Electrodynamic Vibration Exciter
- High-Speed, Micron-Level Positioning System with Variable Coulomb Friction
- Ball-on-Plate Balancing System
- Hydraulically-Balanced Beam System
- Ball-on-Beam Balancing System
- Drive-Train Friction/Backlash/Compliance Testbed

Spring-Pendulum Dynamic System

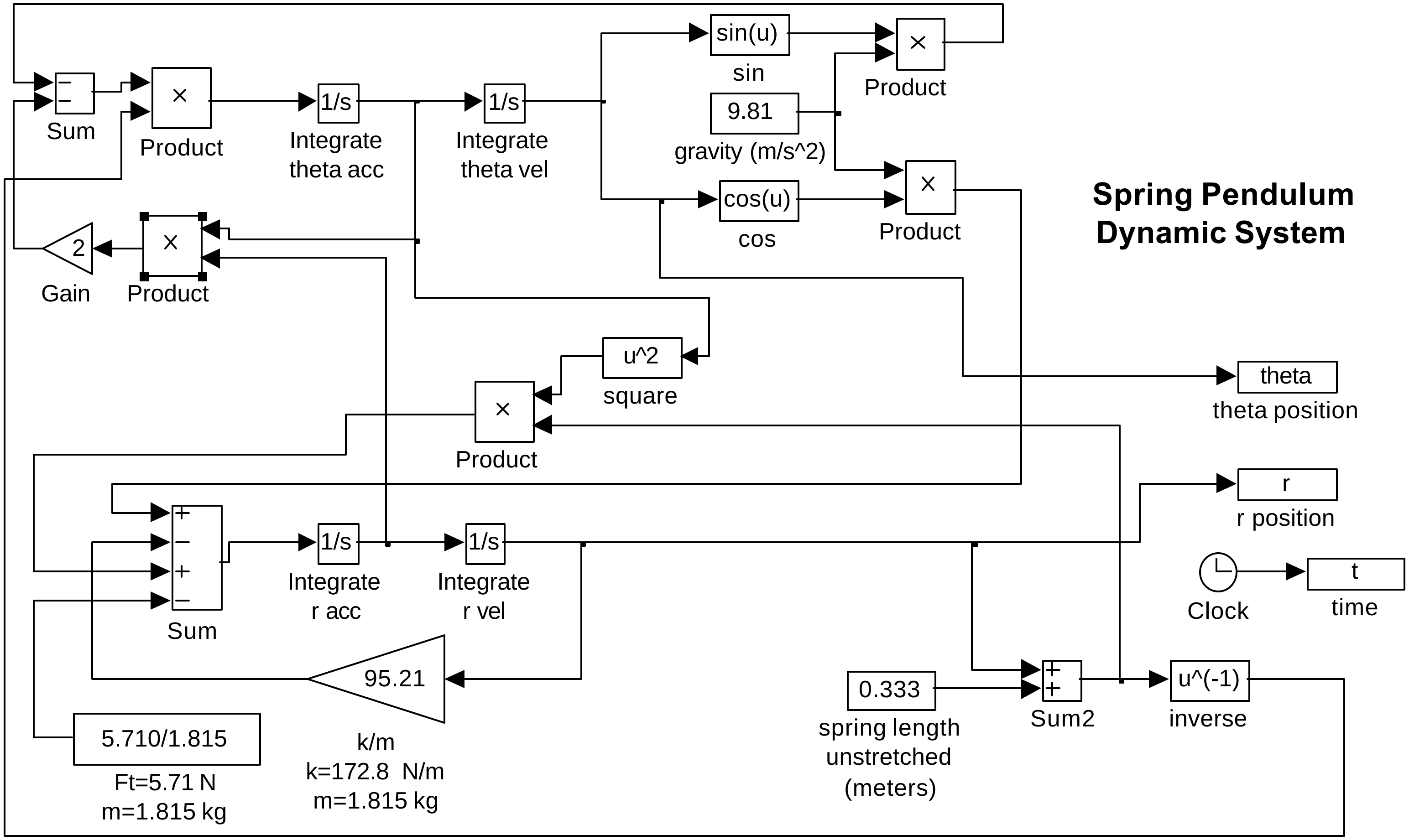




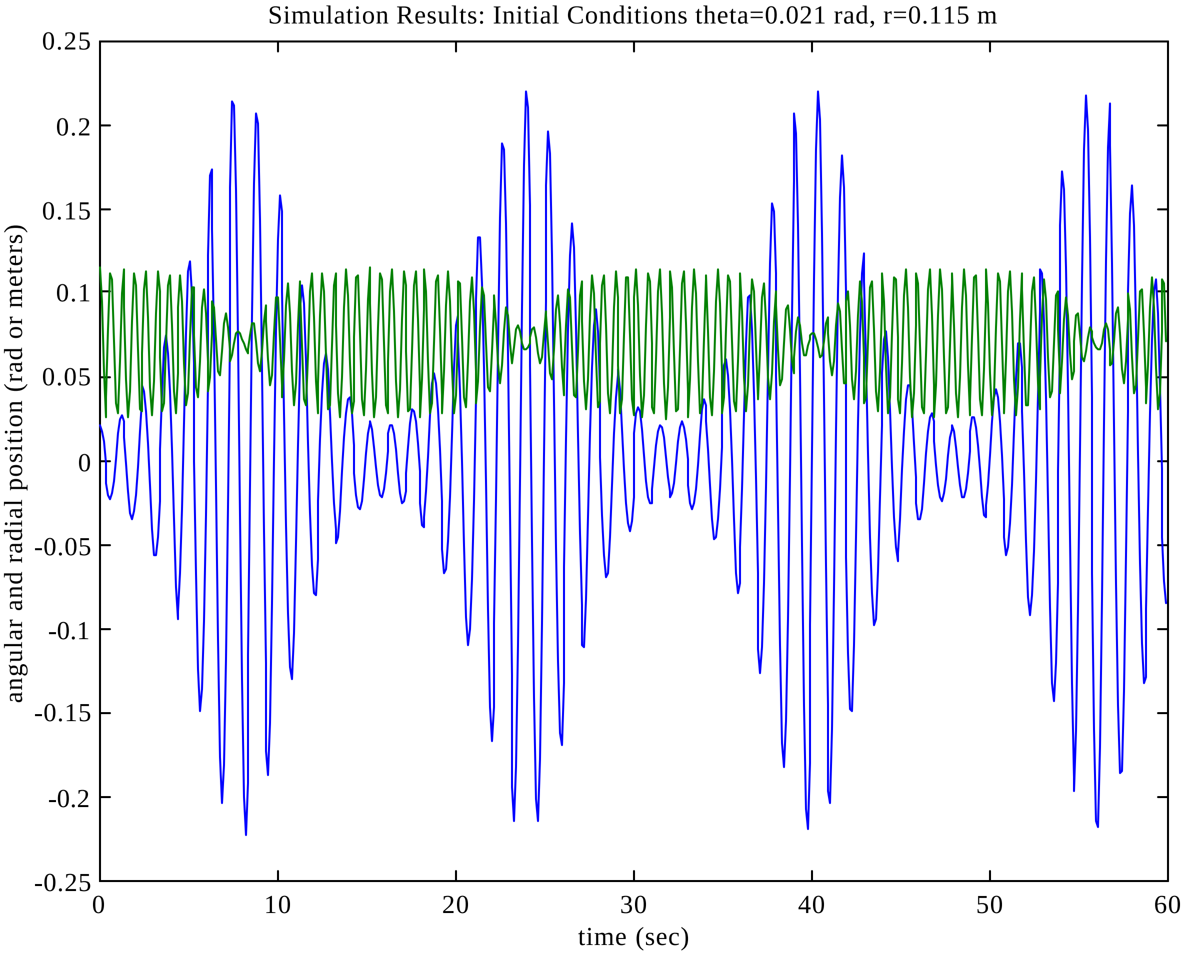
Mathematical Modeling and Analysis of Spring-Pendulum System

$$m\ddot{r} - m(l+r)\dot{\theta}^2 + kr + F_t - mg\cos(\theta) = 0$$

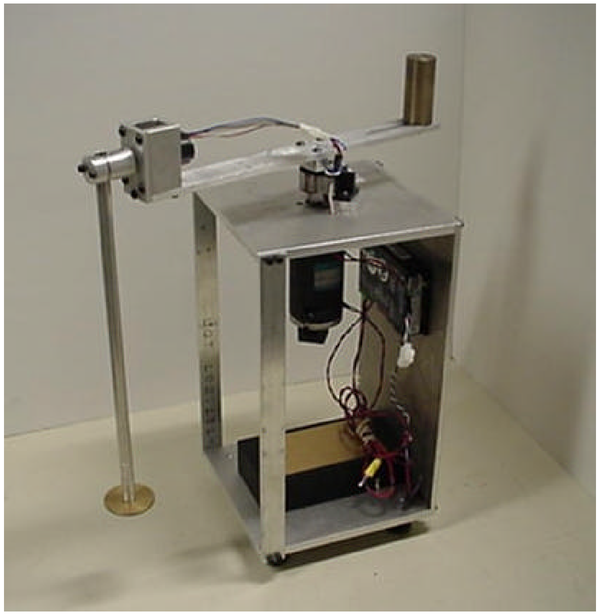
$$(l+r)\ddot{\theta} + 2\dot{r}\dot{\theta} + g\sin(\theta) = 0$$

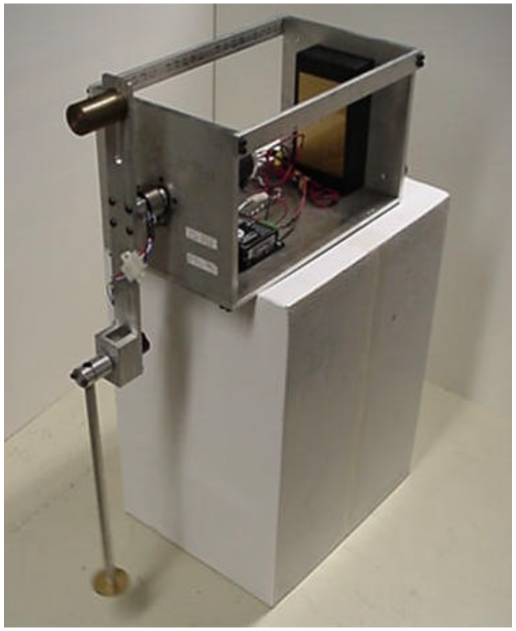


Dynamic Response of Spring-Pendulum System



Inverted-Pendulum Dynamic System: Rotary and Arm-Driven

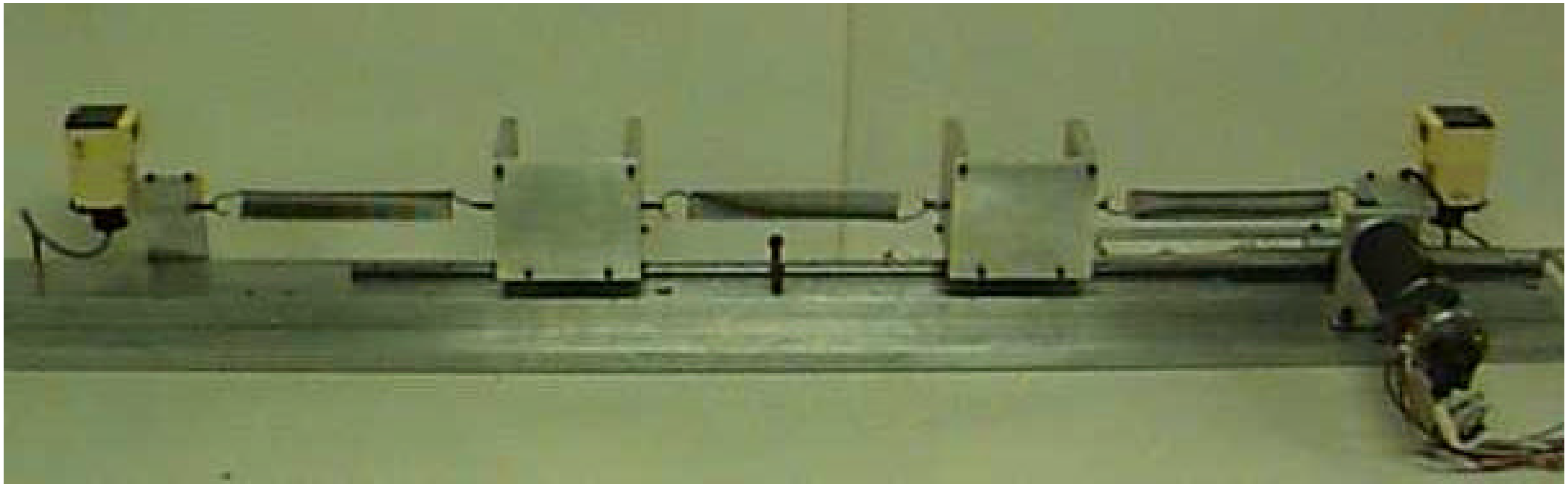




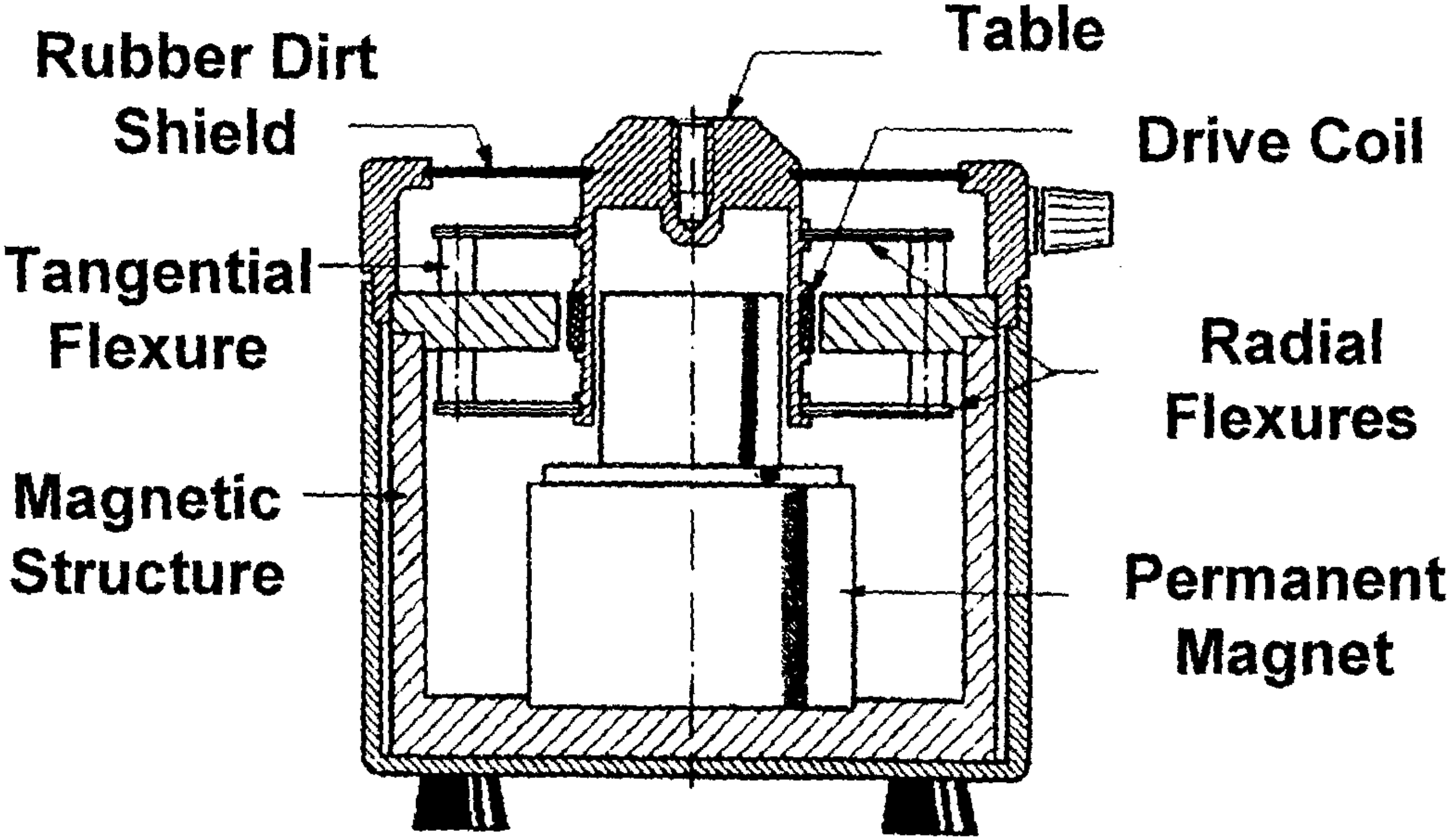
- Brushed DC Motor
- Two Optical Encoders (2000 cpr)
- PWM Servo-Amplifier
- Power Supply
- Pendulum Balancing Control
- Pendulum Swing-Up Control
- Classical, State-Space, and Fuzzy Logic Control
- Converts between Rotary and Arm-Driven Systems
- dSpace Real-Time Control Implementation

Multi-Mass, Multi-Spring Dynamic System

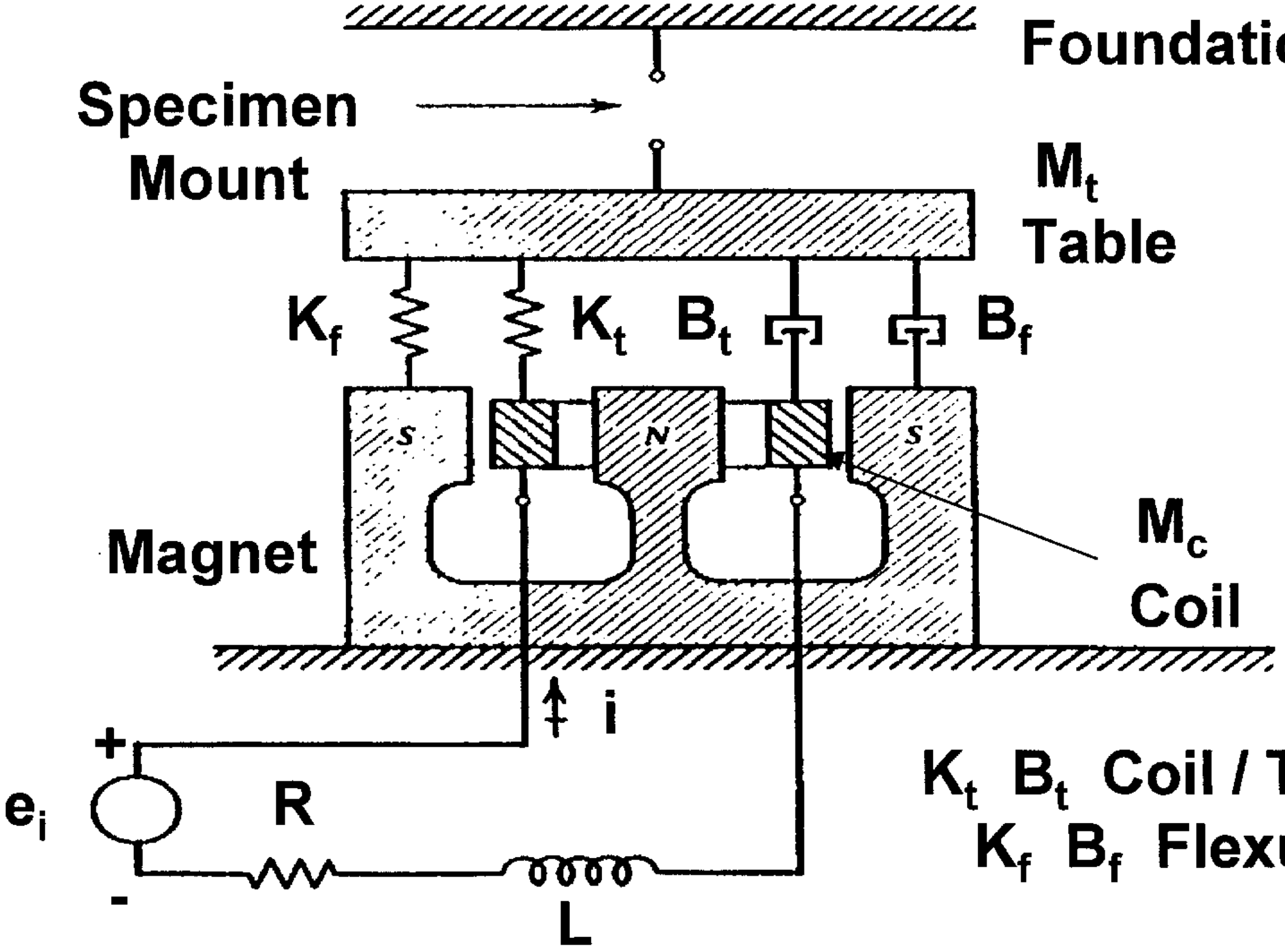
- Brushed DC Motor with Tachometer
- Optical Encoder with 2000 cpr
- Two Infrared Position Sensors
- Free and Forced Vibrations
- System Behavior below, at, and above resonance
- Dynamic Vibration Absorber
- Physical Significance of Transfer Function Poles and Zeros
- Colocated and Non-colocated Control
- dSpace Real-Time Control Implementation



44.5N Electrodynamic Vibration Exciter



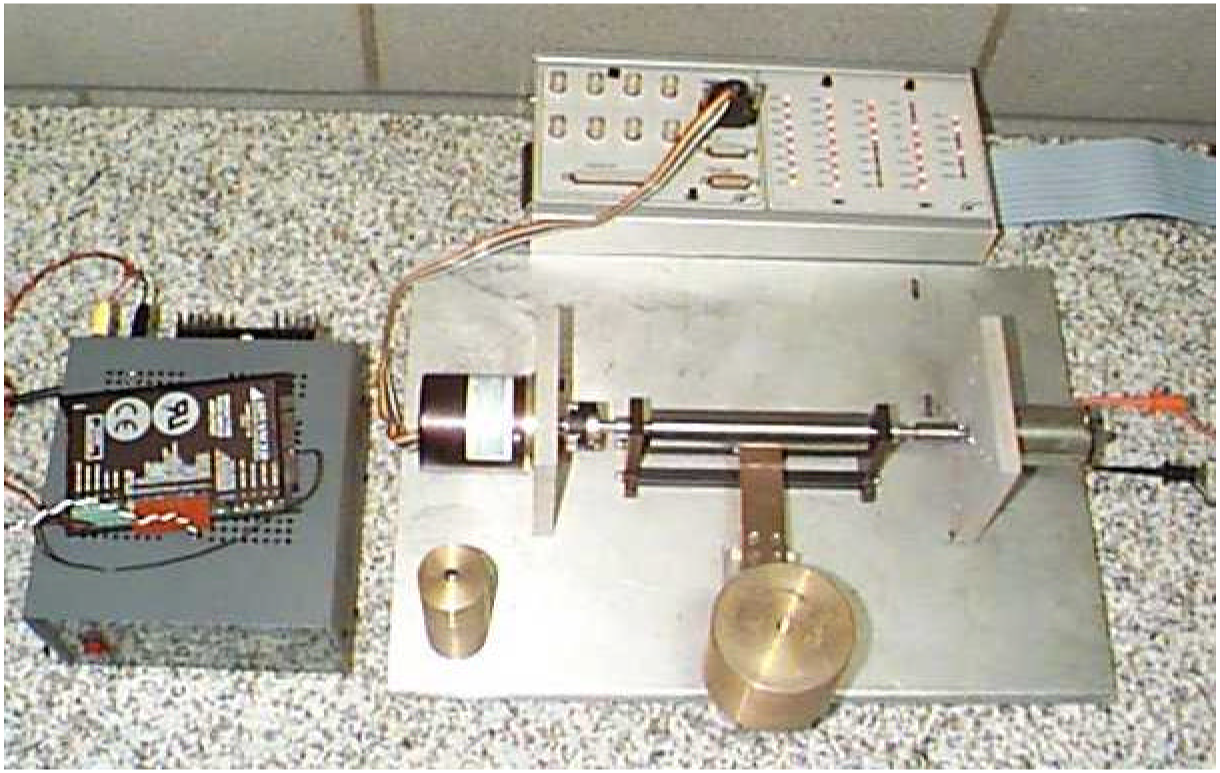
Physical Model of Vibration Shaker



K_t B_t Coil / Table

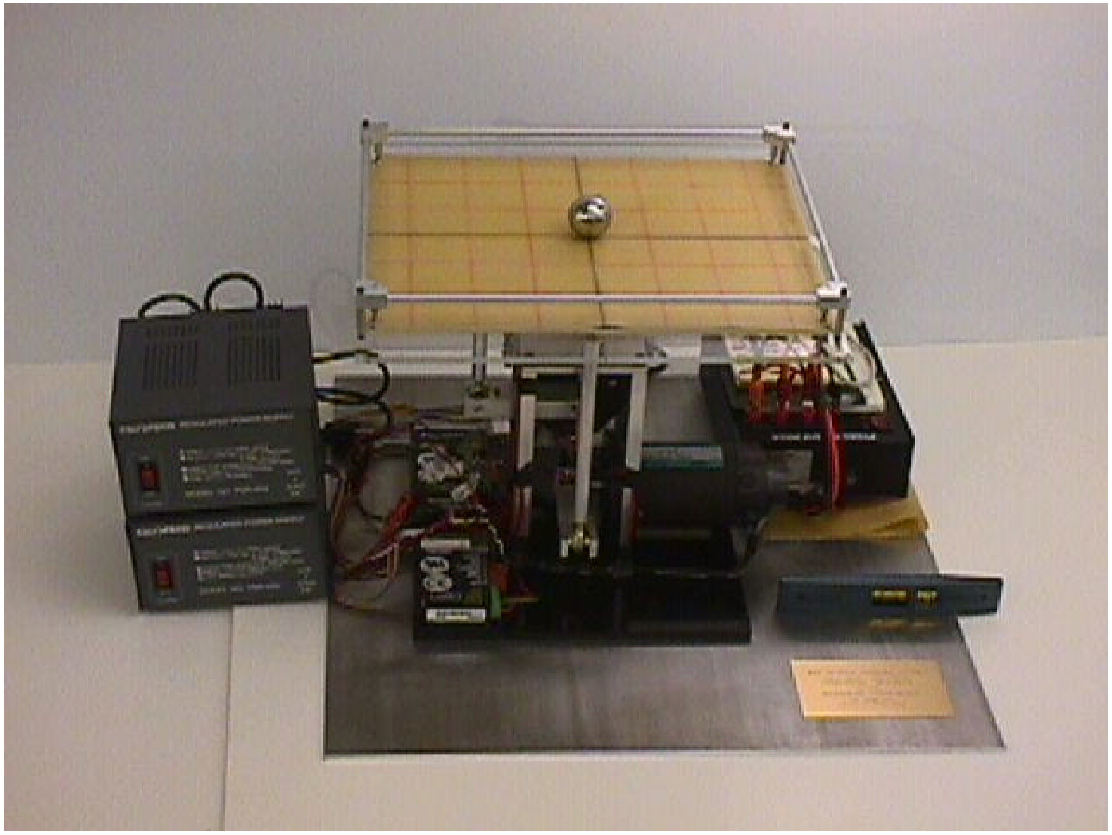
K_f B_f Flexure

High-Speed, Micron-Level Positioning System with Variable Coulomb Friction



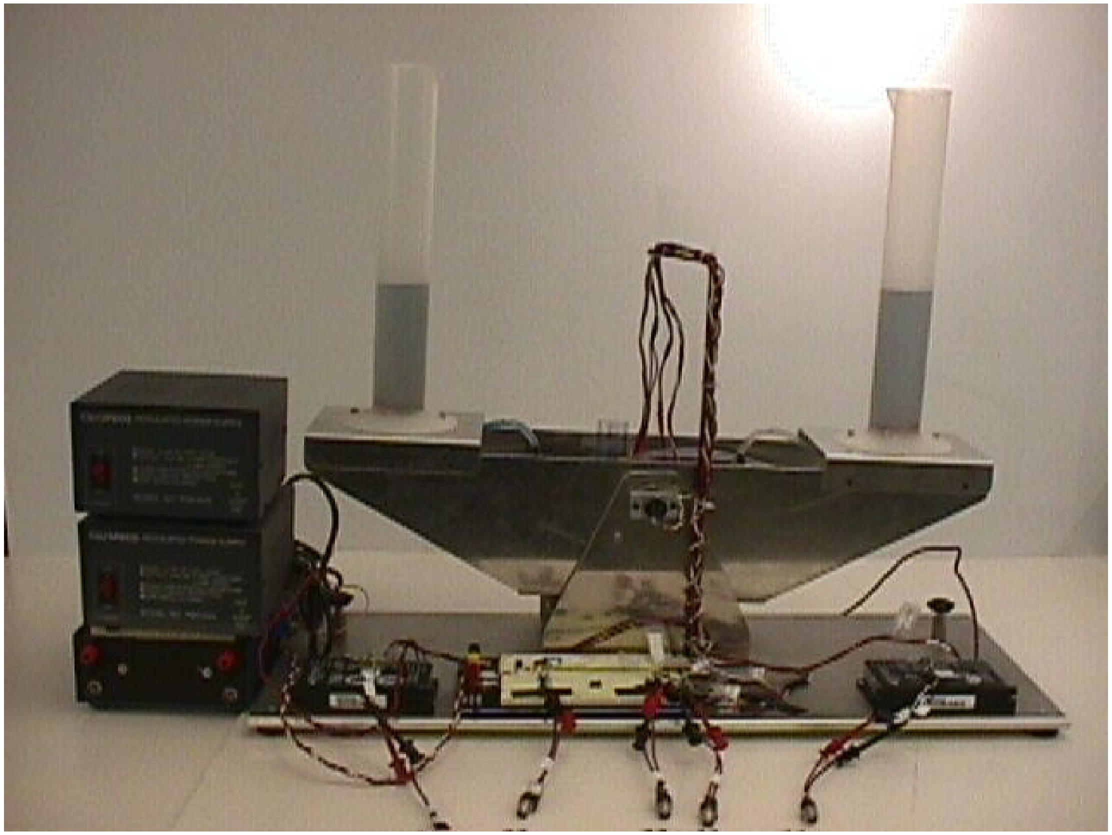
- Actuators:
  - Brushed DC Motor
  - Brushless DC Motor
  - Stepper Motor with microstepping
- 80,000 and 144,000 cpr Optical Encoders
- Coulomb Friction Device
- Variable Inertia
- Direct or Belt Drive
- MatLab Modeling and Control Design Environment
- dSpace Real-Time Control Implementation

Ball-on-Plate Balancing System



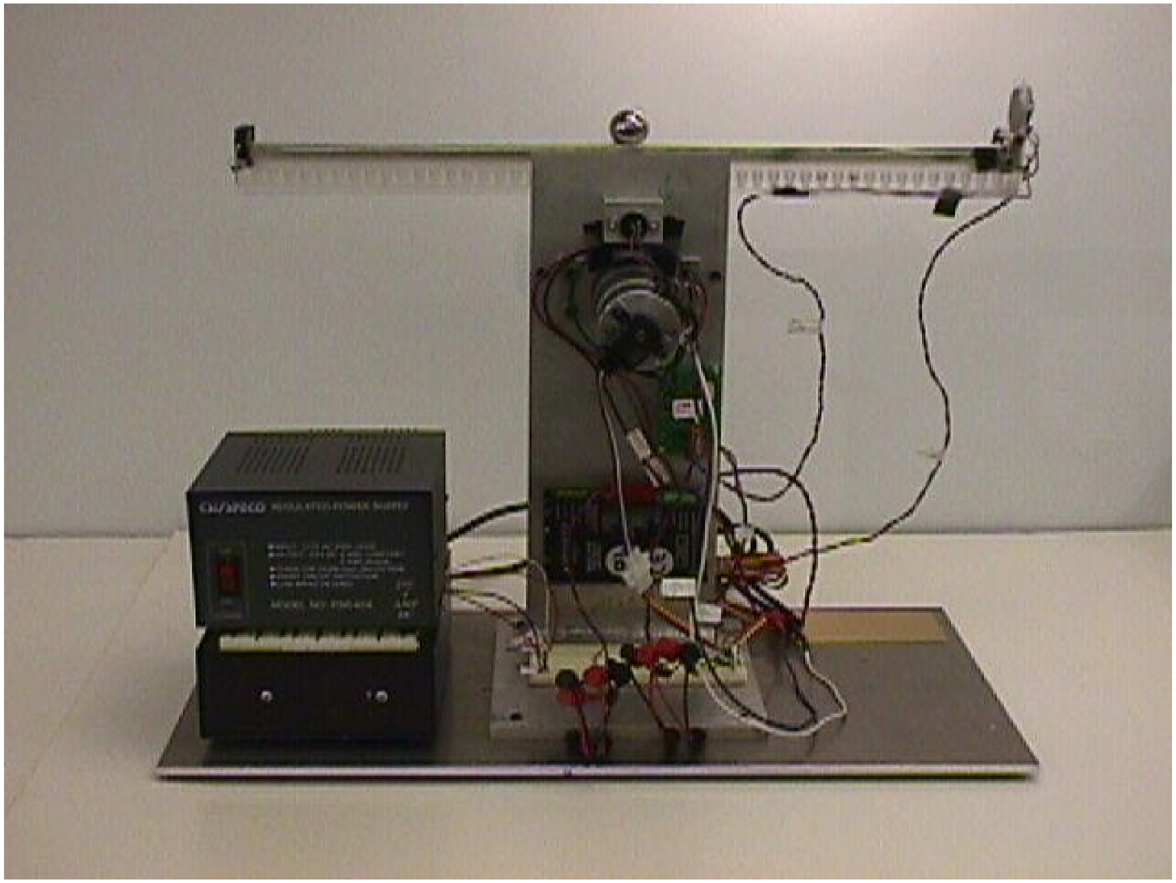
- Two Brushed DC Motors
- Two Optical Encoders (4000 cpr)
- Touch-screen Resistive Ball-Position Sensor
- Two PWM Servo-Amplifiers
- Two Power Supplies
- Disturbance Rejection
- Ball Position Command Tracking, e.g., line, circle, figure eight
- dSpace Real-Time Control Implementation

Hydraulically-Balanced Beam System



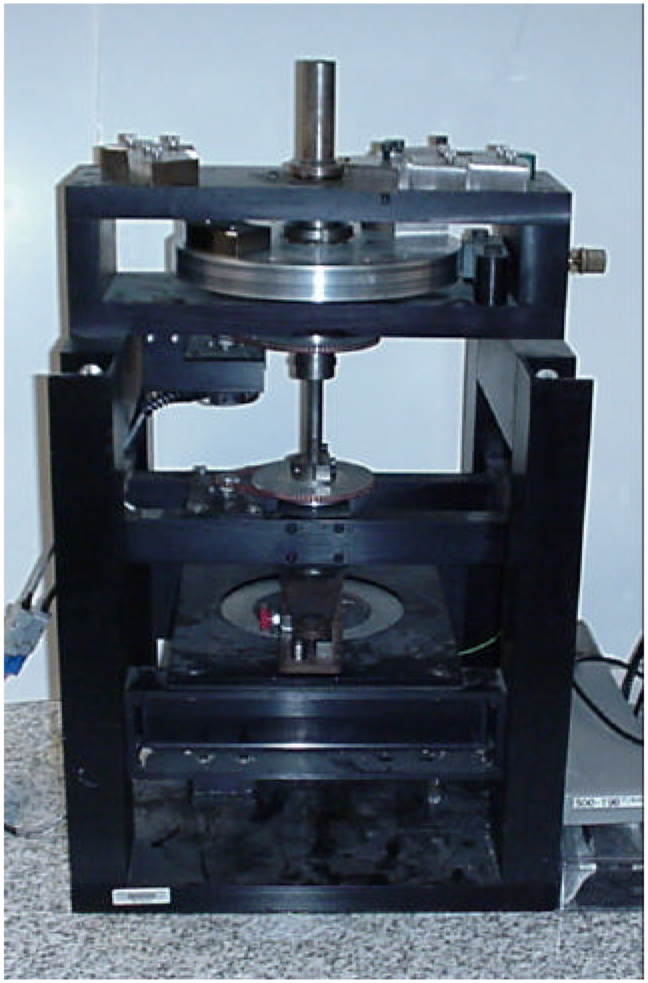
- System Converts between Open-Loop Stable and Open-Loop Unstable Configurations
- Two Gear Pumps
- Two Pressure Sensors at Tank Bases to Determine Liquid Height
- Potentiometer for Beam Angle
- Two PWM Servo-Amplifiers
- Two Power Supplies
- Disturbance Rejection
- Position and Velocity Command Tracking
- Linear and Nonlinear Control Techniques
- dSpace Real-Time Control Implementation

Ball-on-Beam Balancing System



- Brushed DC Motor
- Beam Sensors: Optical Encoder, Tachometer, Potentiometer
- Ball Sensors: Ultrasonic, Potentiometer, Phototransistor
- PWM Servo-Amplifier
- Power Supply
- Disturbance Rejection
- Ball Position Command Tracking
- dSpace Real-Time Control Implementation

Drive-Train Friction/Backlash/Compliance Testbed

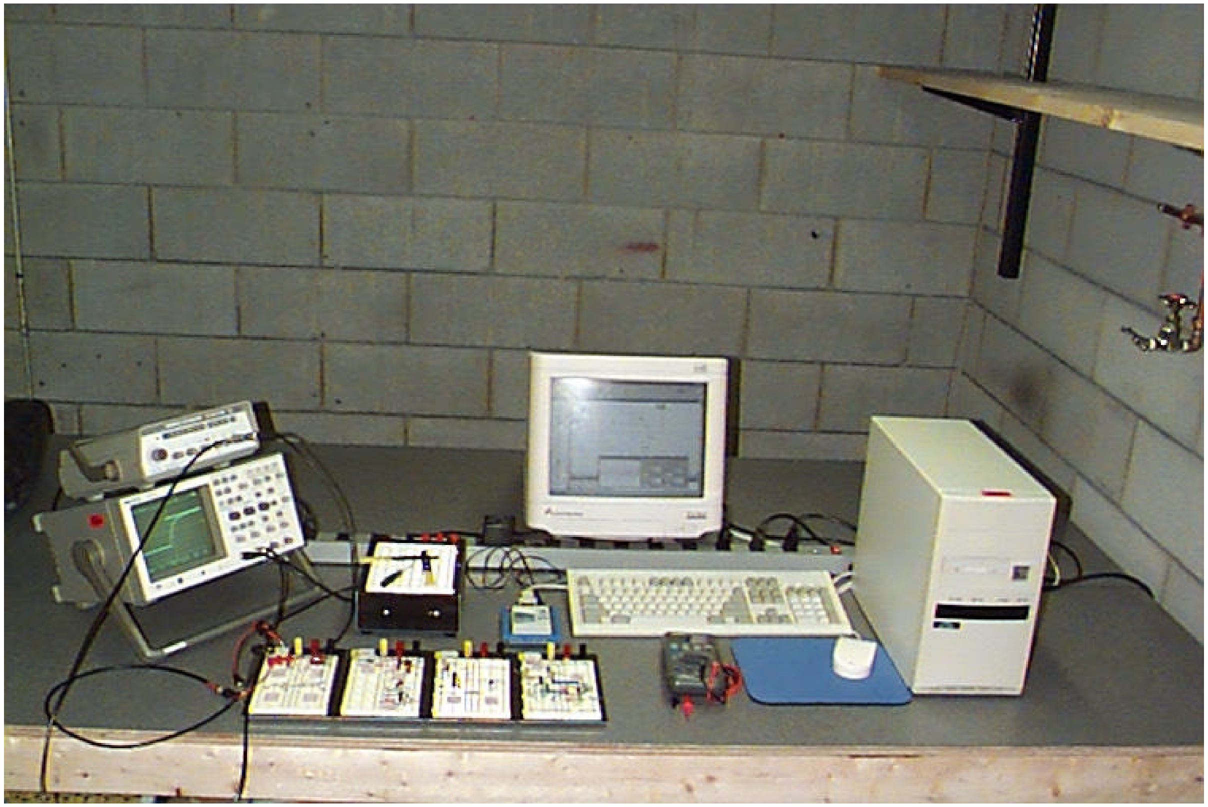


Testbed to Study the Effects of Gear Backlash, Drive-Shaft Compliance, Coulomb Friction & Variable Inertia on Accurate Positioning

Mechatronic System Case Studies

- Thermal System Closed-Loop Temperature Computer Control
- Pneumatic System Closed-Loop Position Computer Control
- Stepper Motor Open-Loop and Closed-Loop Computer Position Control
- DC Motor Closed-Loop Speed Control
  - Analog Control
  - Digital Control with Embedded Microcontroller
- Magnetic Levitation System
- MR Fluid Rotary Damper System

Two-Person Mechatronics Laboratory Station



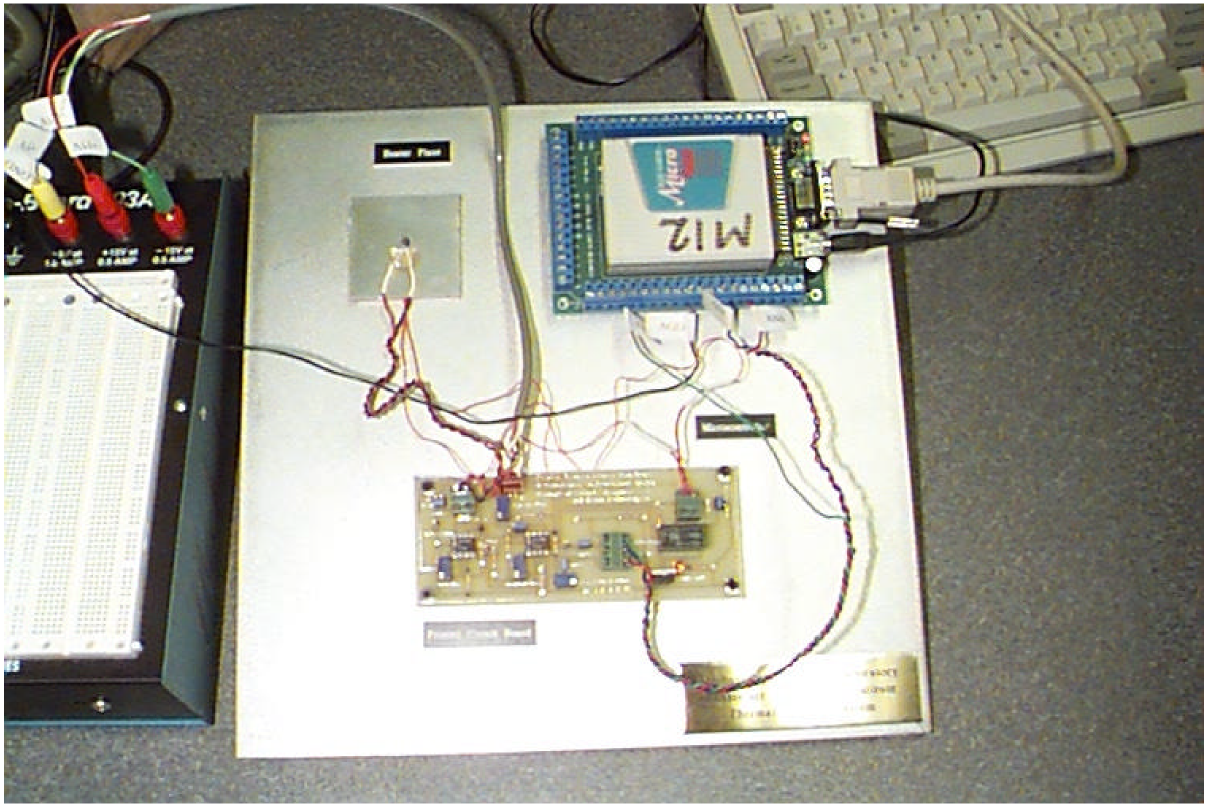
- Pentium Computer with MATLAB, Electronics Workbench, and Working Model
- Function Generator
- Digital Oscilloscope
- Multimeter
- Powered Protoboard
- Microcontroller
- Assorted analog / digital sensors, actuators and components

Blue Earth Micro 485 Specifications

Blue Earth Micro 485 Specifications

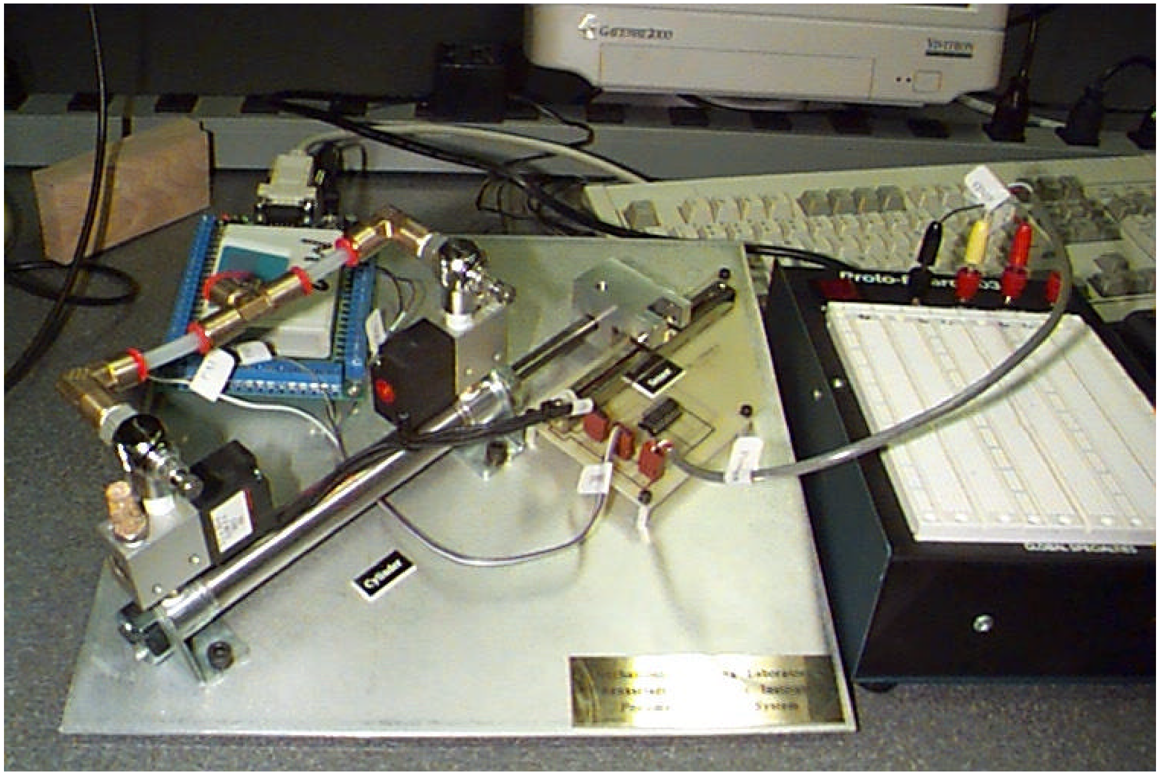
Feature	**Specification**
Microprocessor	Intel 8051 running at 12 MHz
Digital I/O	27 Bi-directional TTL compatible pins
Analog Inputs	4 12-bit 0-5 volt A/D converter channels
Serial Communication	RS-422, RS-232
RAM	128K, battery-backed for retention after power down
ROM	32K, contains on-board Basic and Monitor

Thermal System Closed-Loop Temperature Control



- aluminum plate
- thin-film resistive heater
- ceramic insulation
- conduction and convection heat transfer
- AD590 temperature sensor
- microcontroller
- on-off closed-loop control with relay
- support analog electronics

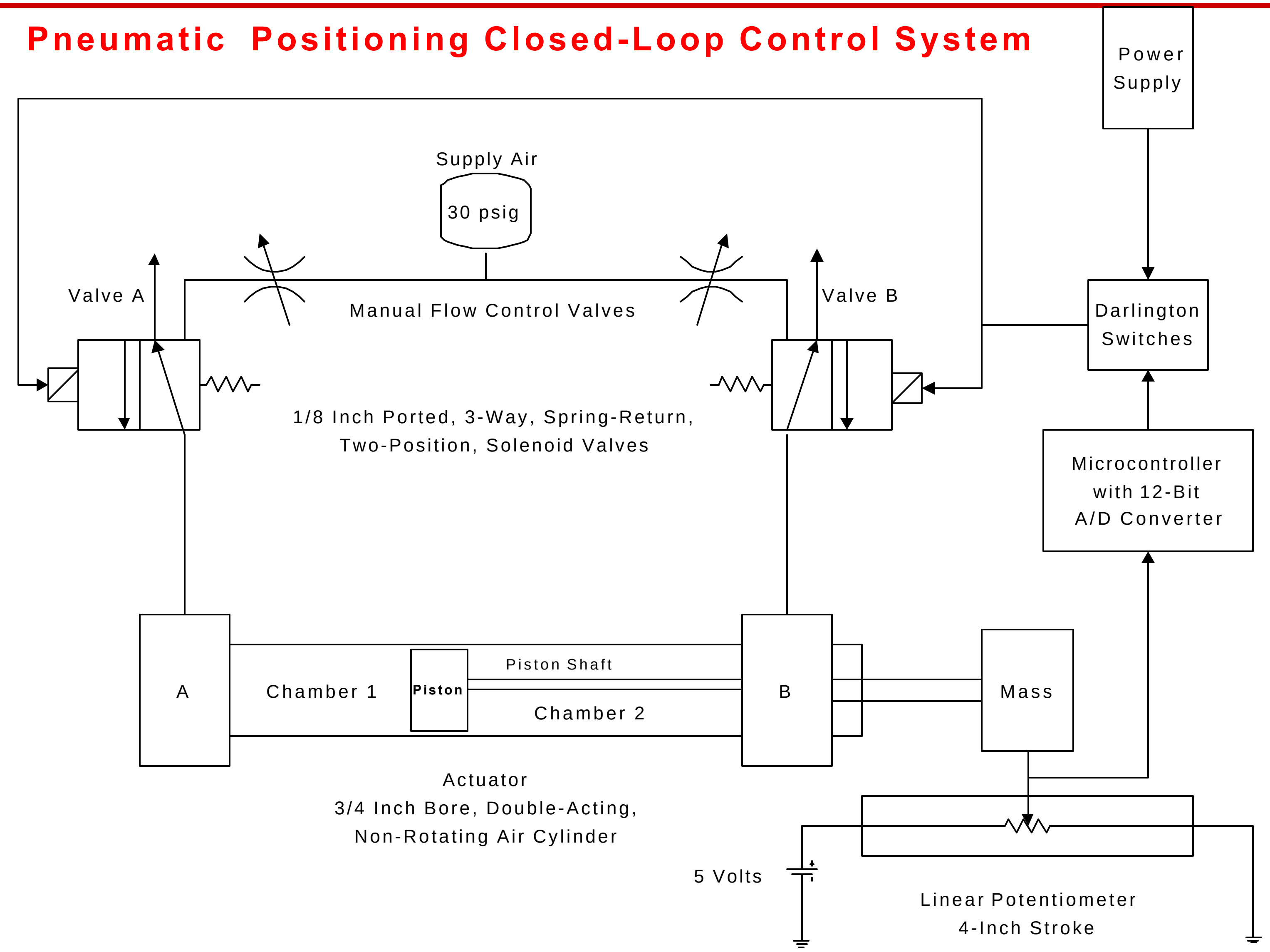
Pneumatic System Closed-Loop Position Control



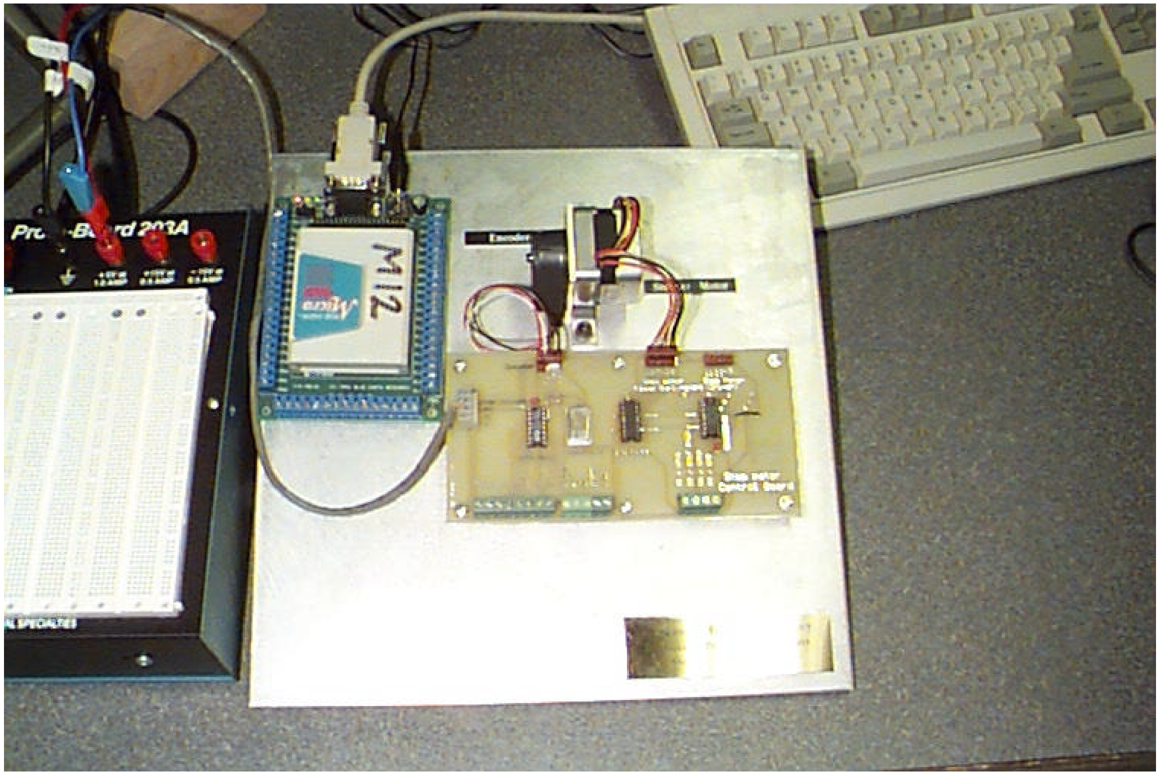
- 3/4” bore, double-acting, non-rotating air cylinder
- linear potentiometer to measure mass position
- 30 psig air supply
- two flow-control valves
- two 1/8”ported, 3-way, spring-return, two-position solenoid valves
- Darlington switches to energize solenoids
- microcontroller
- on-off, modified on-off, PWM closed-loop control

Schematic of Pneumatic Servomechanism

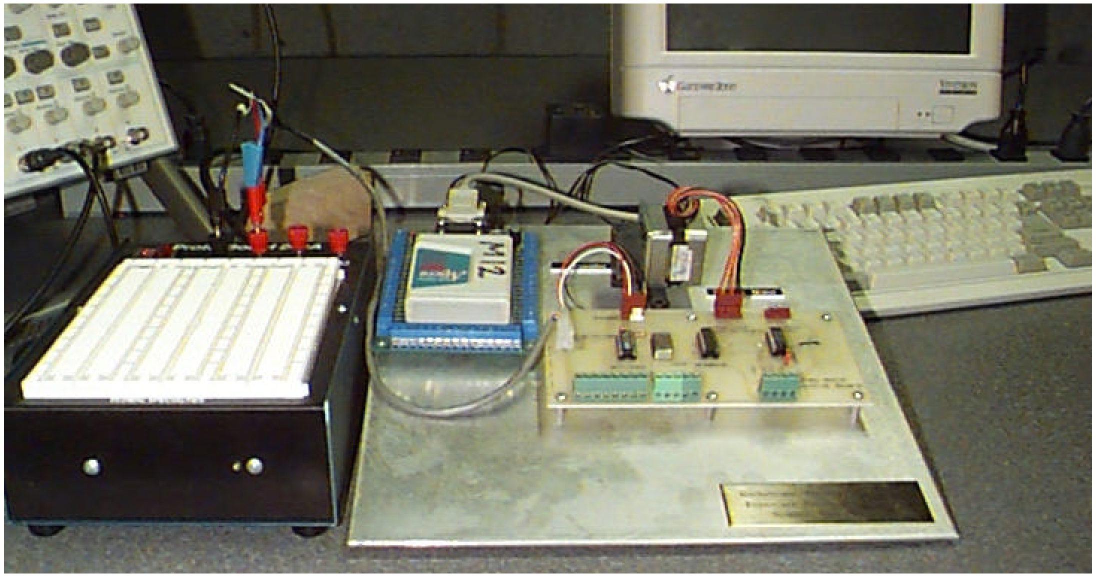
Pneumatic Positioning Closed-Loop Control System



Stepper Motor
Open-Loop and Closed-Loop Control

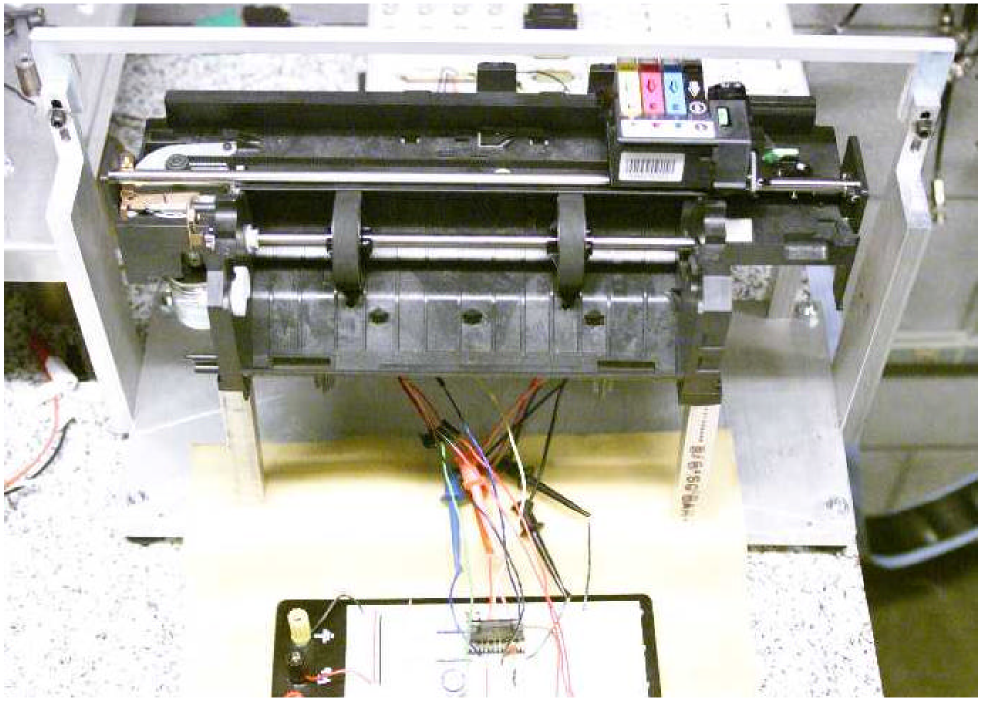


- stepper motor
- optical encoder
- microcontroller
- electronics to interface the microcontroller to the motor and encoder
- full-step and half-step operation
- control via a Quad-Darlington IC
- control via a step-motor-driver IC
- programming in Basic or C

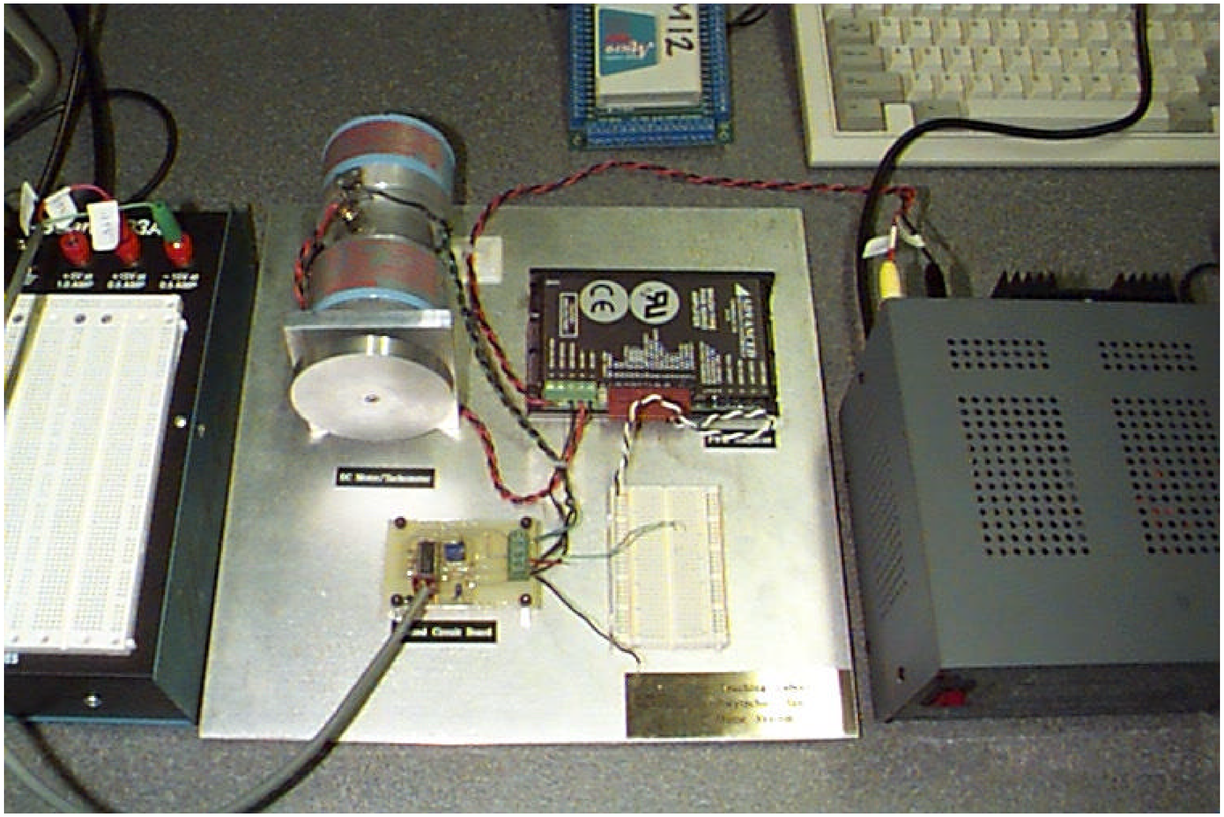


Stepper Motor System Design: Ink-Jet Printer Application

Stepper Motor Open-Loop and Closed-Loop Control

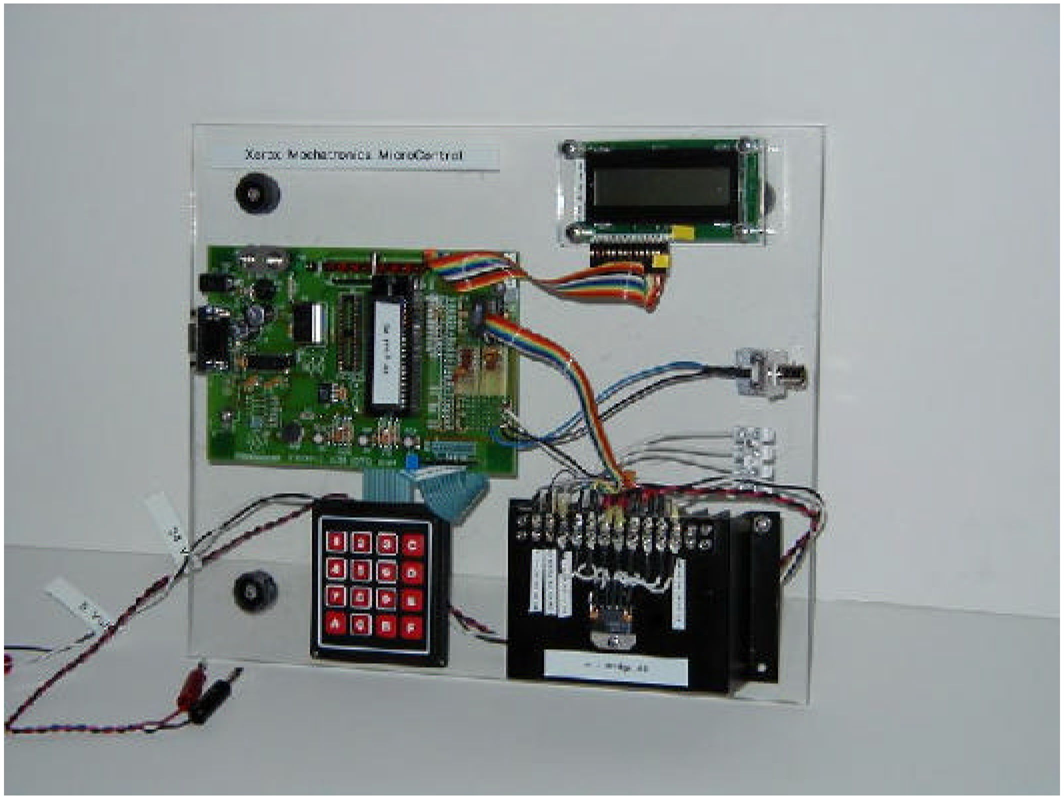


DC Motor Closed-Loop Speed Control



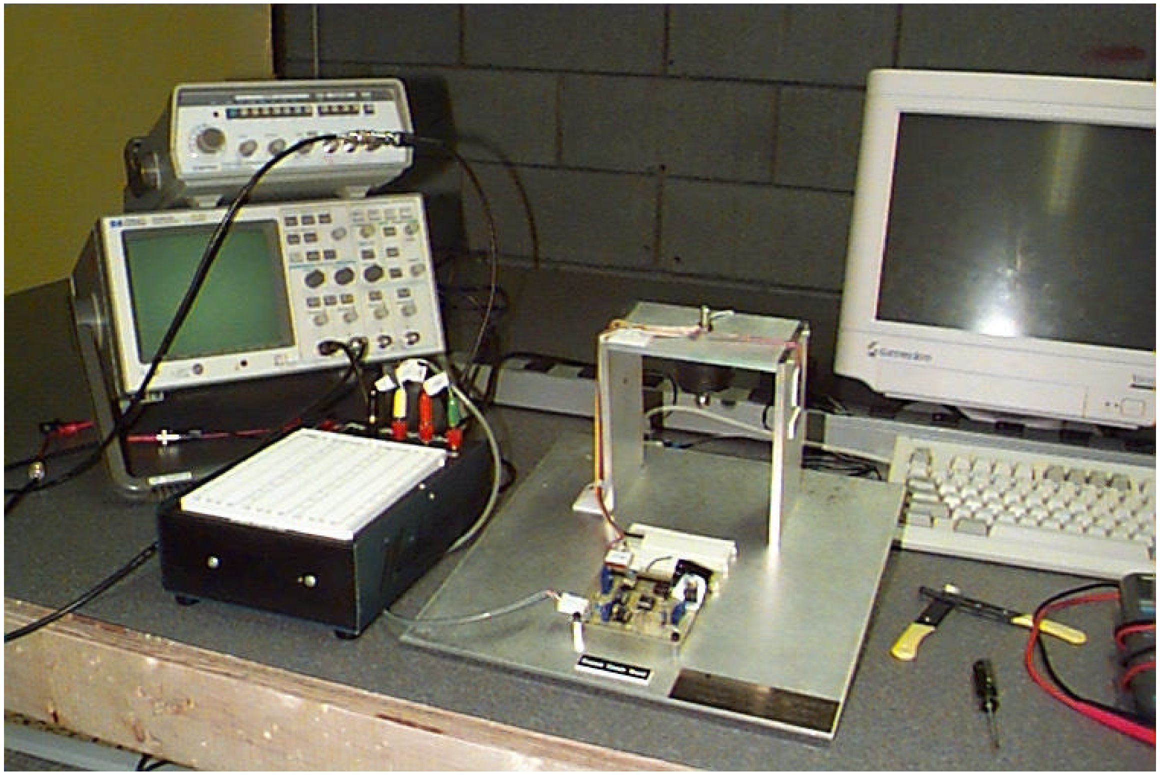
- Permanent-magnet brushed DC motor
- integral analog tachometer
- aluminum disk load inertia
- PWM power amplifier
- 24-volt, 4-amp power supply
- analog control design and implementation: lead, lag, lead-lag

Microcontrol Motor-Speed-Control Testbed



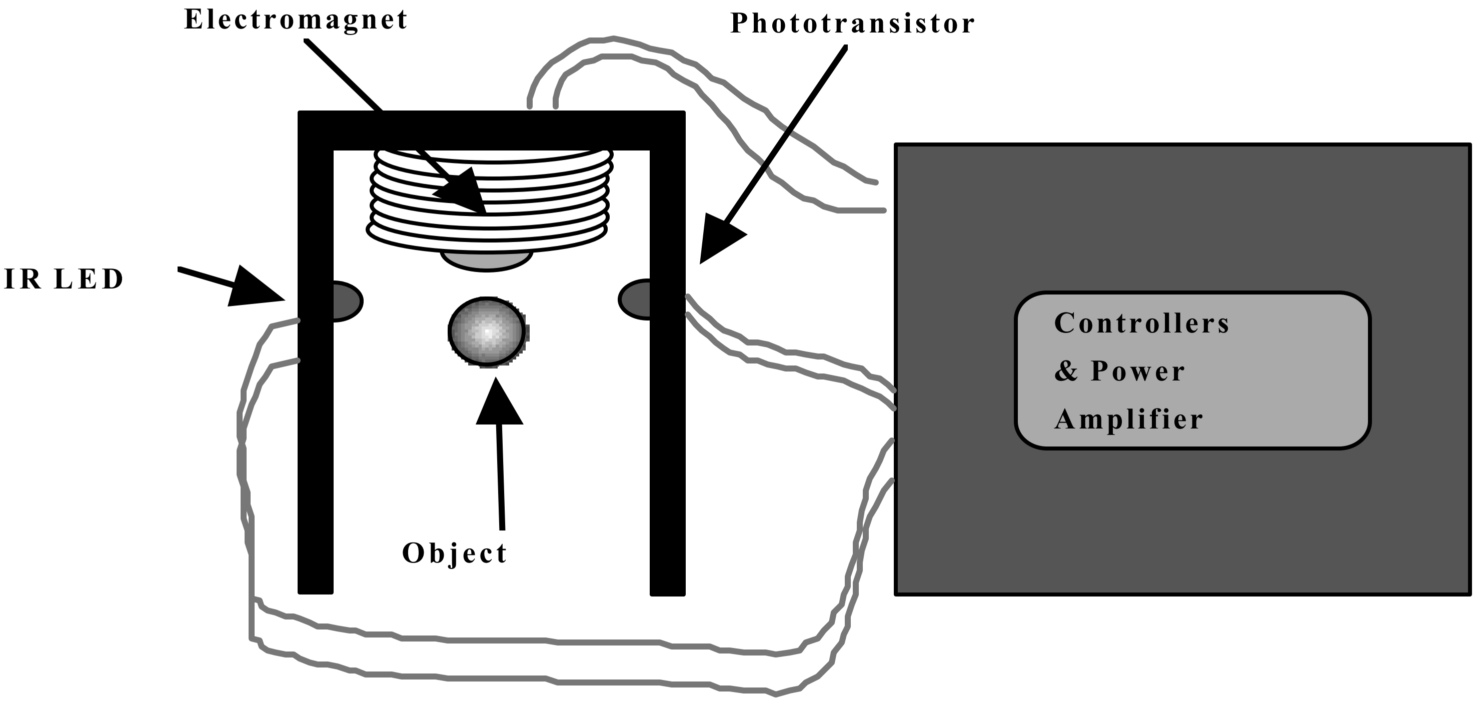
- Two embedded microcontrollers from MicroChip Inc. configured for: 3 channel 8-bit analog / digital (A/D) acquisition , 10-bit pulse-width-modulated (PWM) drive, serial communication to PC, general purpose digital I/O
- High power H-bridge for output stage of pulse-width-modulated (PWM) driver (for d.c. motors)
- Hex keypad for data entry
- Liquid crystal display (LCD) for data display
- Analog electronics (op amps) for measuring tachometer and input reference signal

Magnetic Levitation System

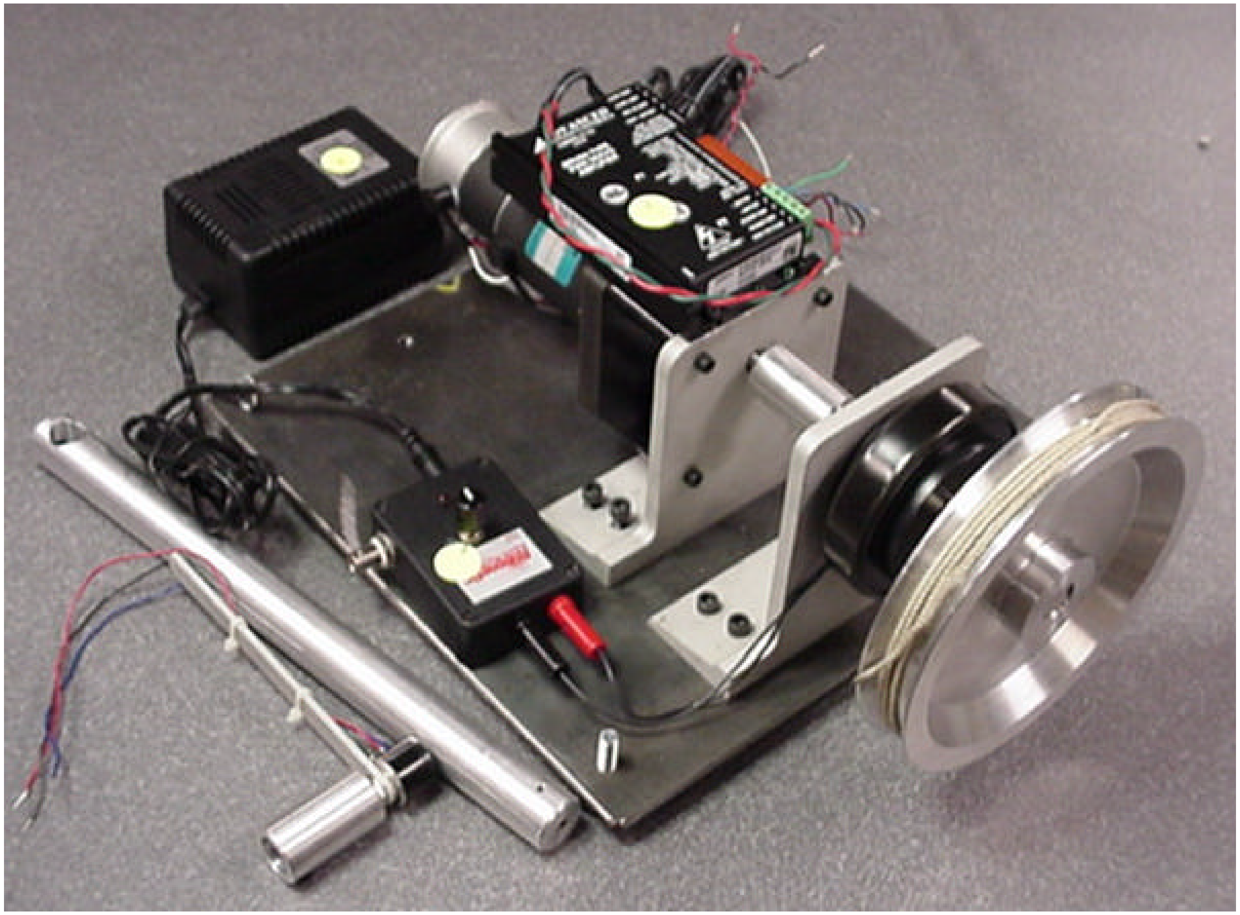


- Magnetically-levitated 1/2”-diameter steel ball
- electromagnet actuator: 1/4” steel screw with 3000 turns of 26-gauge wire
- gap sensor: infra-red diode emitter and phototransistor detector
- TIP-31, NPN, bipolar transistor as a current amplifier
- ±15 volt, +5 volt power supply
- analog lead controller design and implementation

Schematic Of
Magnetic Levitation System



Mechanical System Digital Speed Control using DC Motor with MR Fluid Brake



- MR Fluid Rotary Damper
- Brushed DC Motor with Gearbox
- Motor Tachometer
- Shaft Potentiometer
- Current Controller
- PWM Power Amplifier
- 24-Volt, 4-Amp Power Supply
- AC/DC Adapter
- Pulley / Arm Attached to MR Fluid Brake
- Microcontroller with D/A Converter

All these systems are industrially relevant and require a complete dynamic system investigation with a balance between modeling / analysis and hardware implementation.

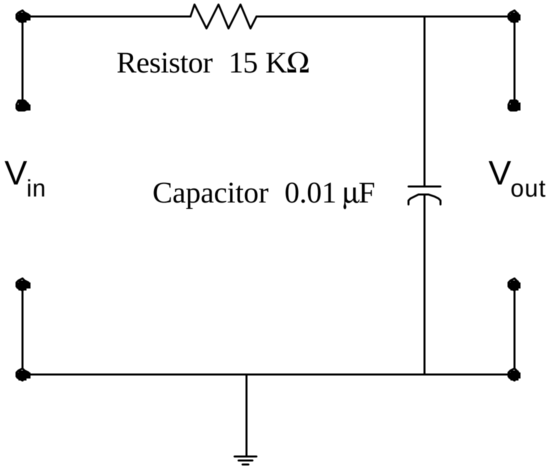
Only a Mechatronics engineer can accomplish this!

Mechatronics
Exercise Examples

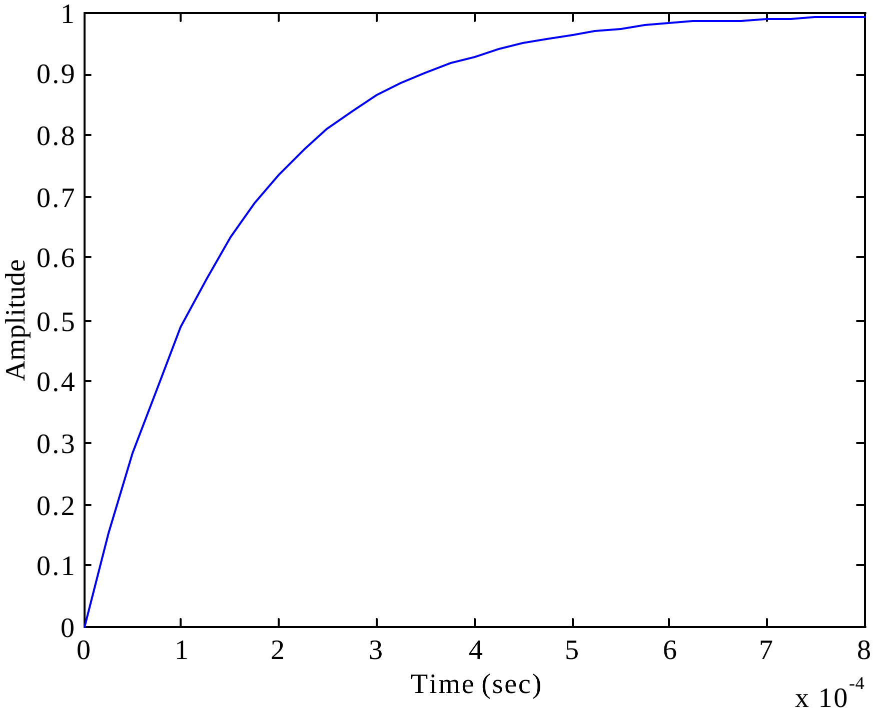
- Analog Electronics: Time Response, Frequency Response, Loading Effects
- Dynamic System Modeling and Analysis: Space Station Solar Alpha Rotary Joint
- Modeling, Analysis, and Control of an Electrohydraulic Valve-Controlled Servomechanism

Analog Electronics:
RC Low-Pass Filter
Time Response &
Frequency Response

$$\frac{V_{out}}{V_{in}} = \frac{1}{RCs+1}$$

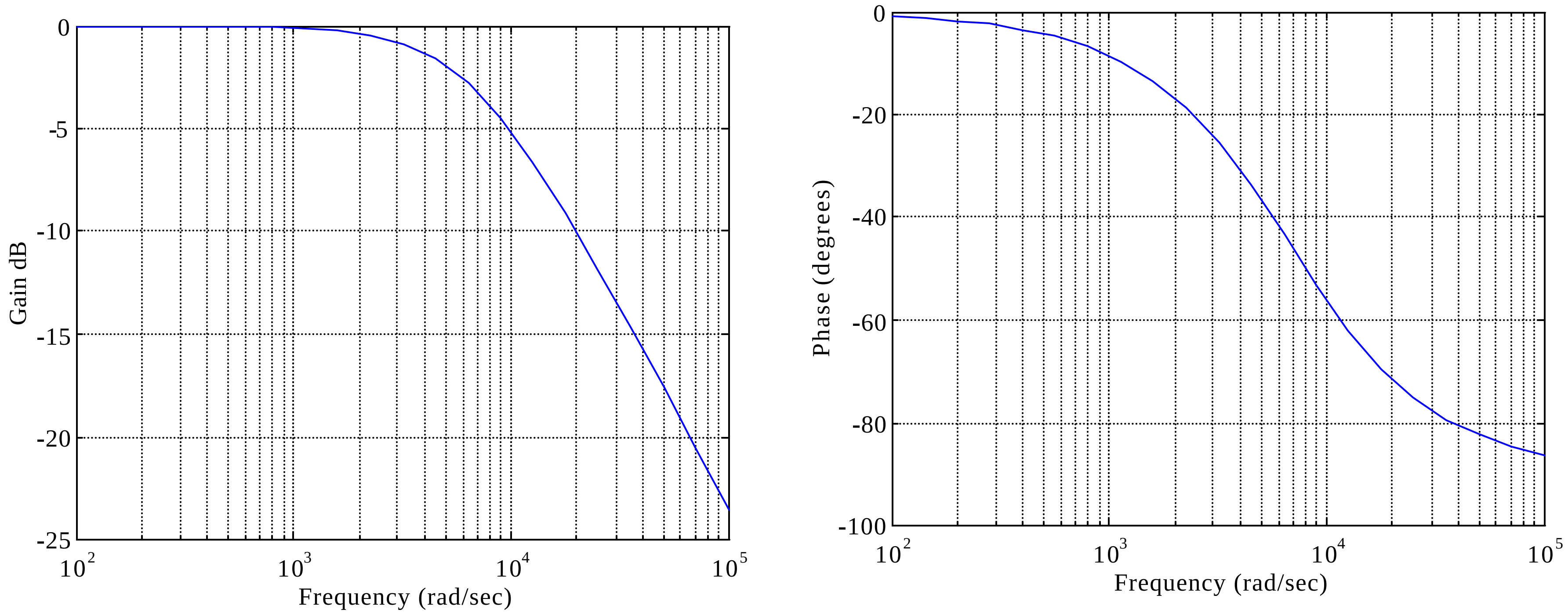


Time Response



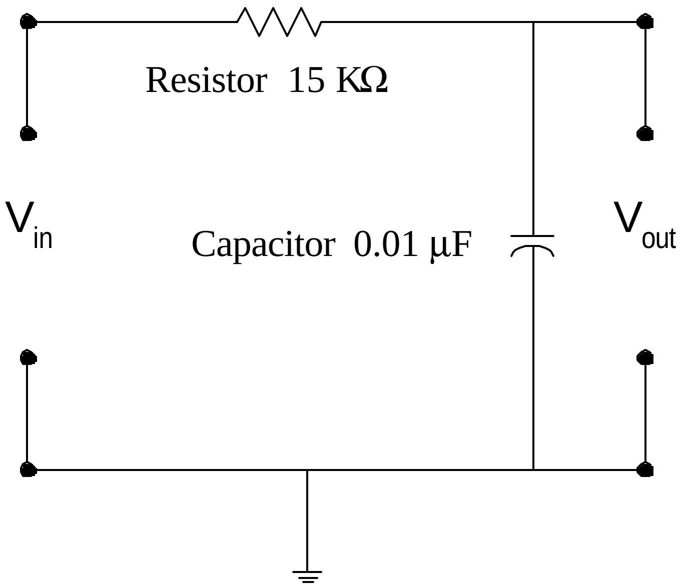
Time Constant τ = RC

Frequency Response



Bandwidth = $1/\tau$

Analog Electronics: Loading Effects



$$\begin{bmatrix} V_{in} \\ i_{in} \end{bmatrix} = \begin{bmatrix} RCs+1 & -R \\ Cs & -1 \end{bmatrix} \begin{bmatrix} V_{out} \\ i_{out} \end{bmatrix}$$

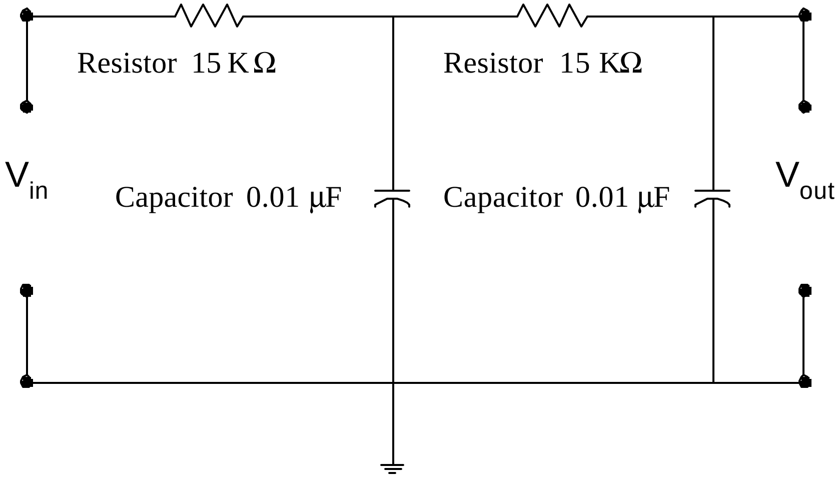
$$\frac{V_{out}}{V_{in}} = \frac{1}{RCs+1} = \frac{1}{\tau s+1} \quad \text{when } i_{out} = 0$$

$$Z_{out} = \left.\frac{V_{out}}{i_{out}}\right|_{V_{in}=0} = \frac{R}{RCs+1} \quad \text{Output Impedance}$$

$$Z_{in} = \left.\frac{V_{in}}{i_{in}}\right|_{i_{out}=0} = \frac{RCs+1}{Cs} \quad \text{Input Impedance}$$

RC Low-Pass Filter

2 RC Low-Pass Filters in Series



$$\frac{V_{out}}{V_{in}} \neq G(s)_{1-unloaded}\, G(s)_{2-unloaded} = \left(\frac{1}{RCs+1}\right)\left(\frac{1}{RCs+1}\right)$$

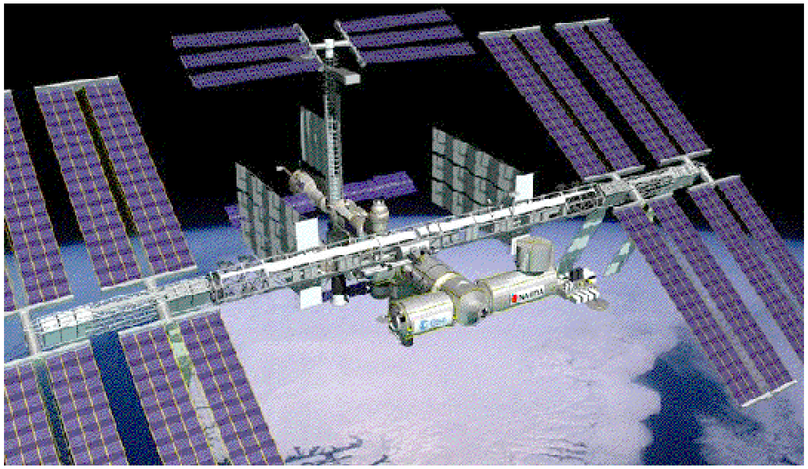
$$\frac{V_{out}}{V_{in}} = G(s)_{1-loaded}\, G(s)_{2-unloaded}$$

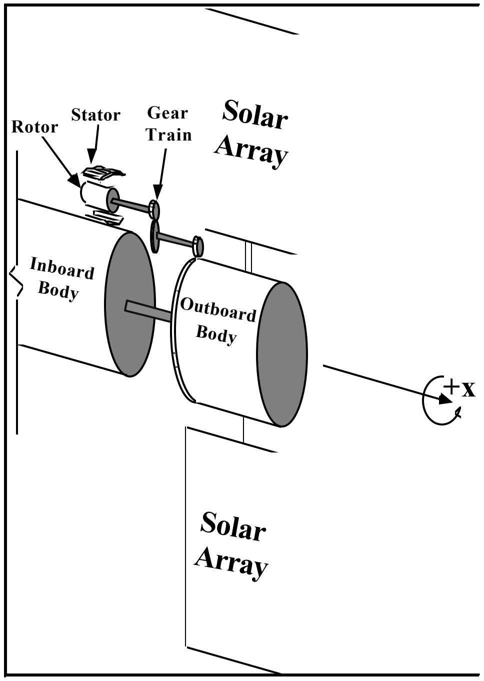
$$= \left(\frac{1}{RCs+1}\right)\left(\frac{1}{1+\frac{Z_{out-1}}{Z_{in-2}}}\right)\left(\frac{1}{RCs+1}\right)$$

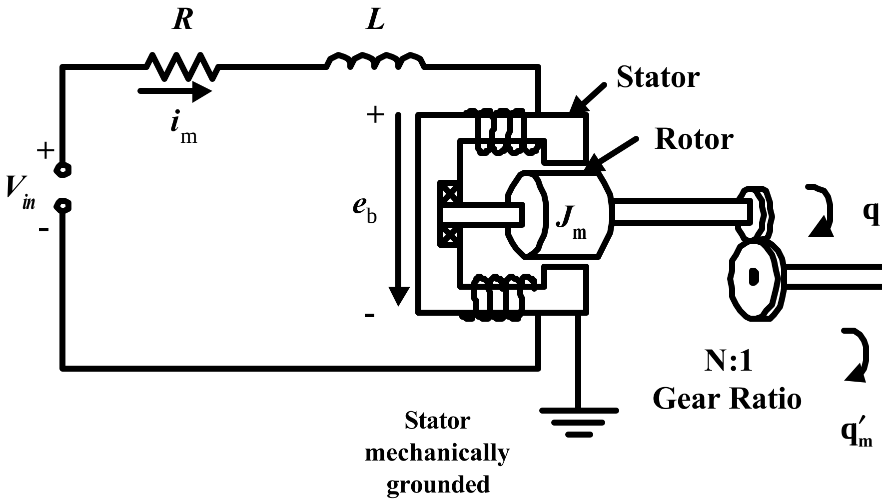
$$= \frac{1}{(RCs+1)^2 + RCs}$$

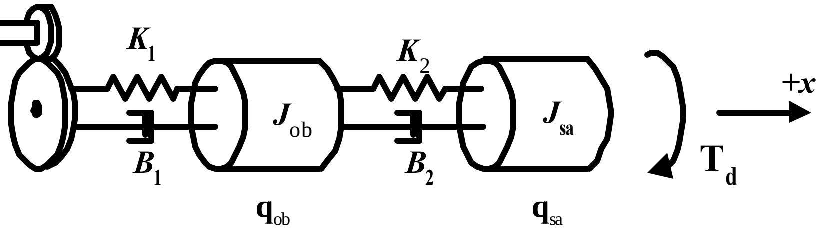
Only if $Z_{out\text{-}1} << Z_{in\text{-}2}$ for the frequency range of interest will loading effects be negligible.

Space Station Solar Alpha Rotary Joint: Physical System and Physical Model





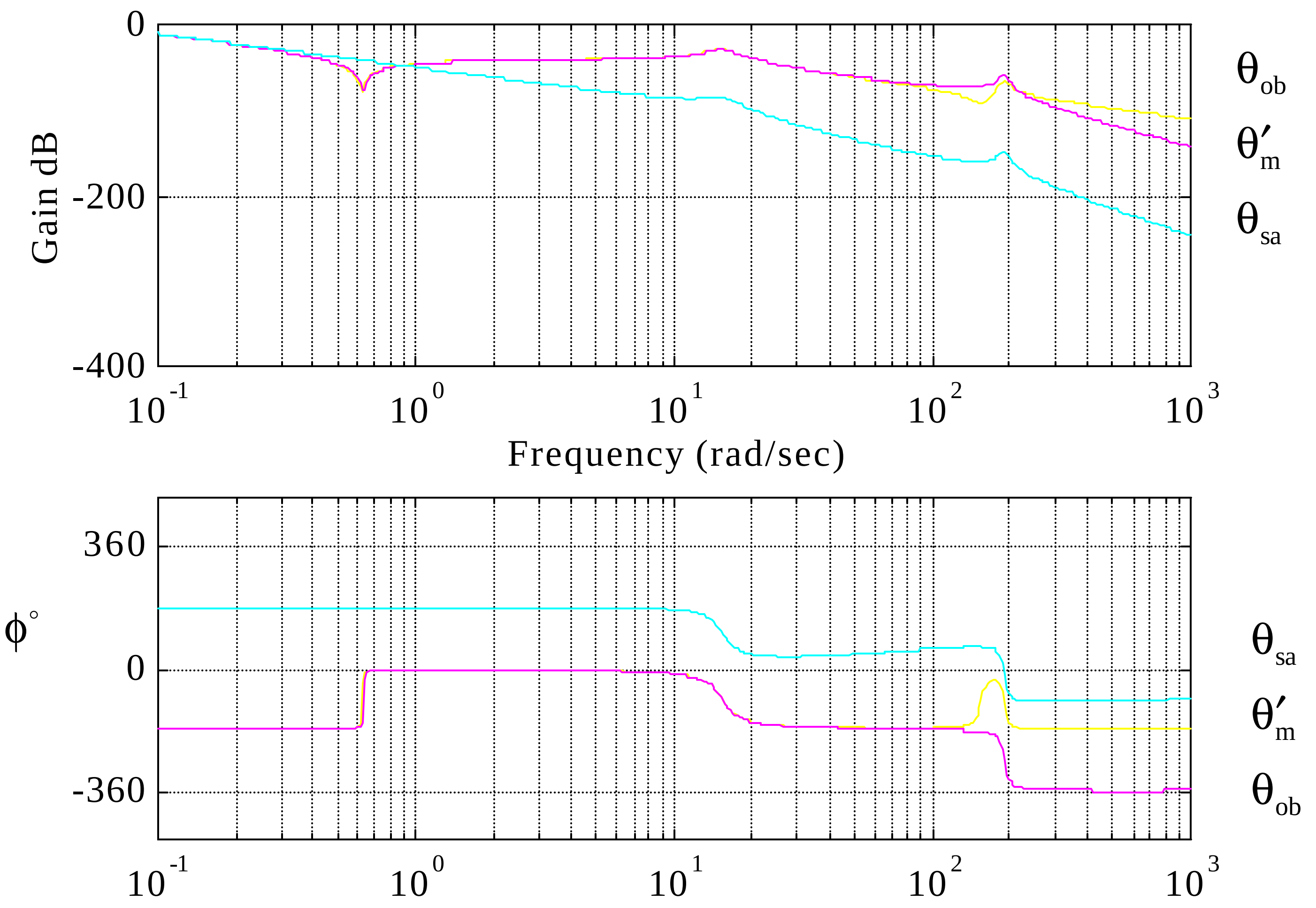




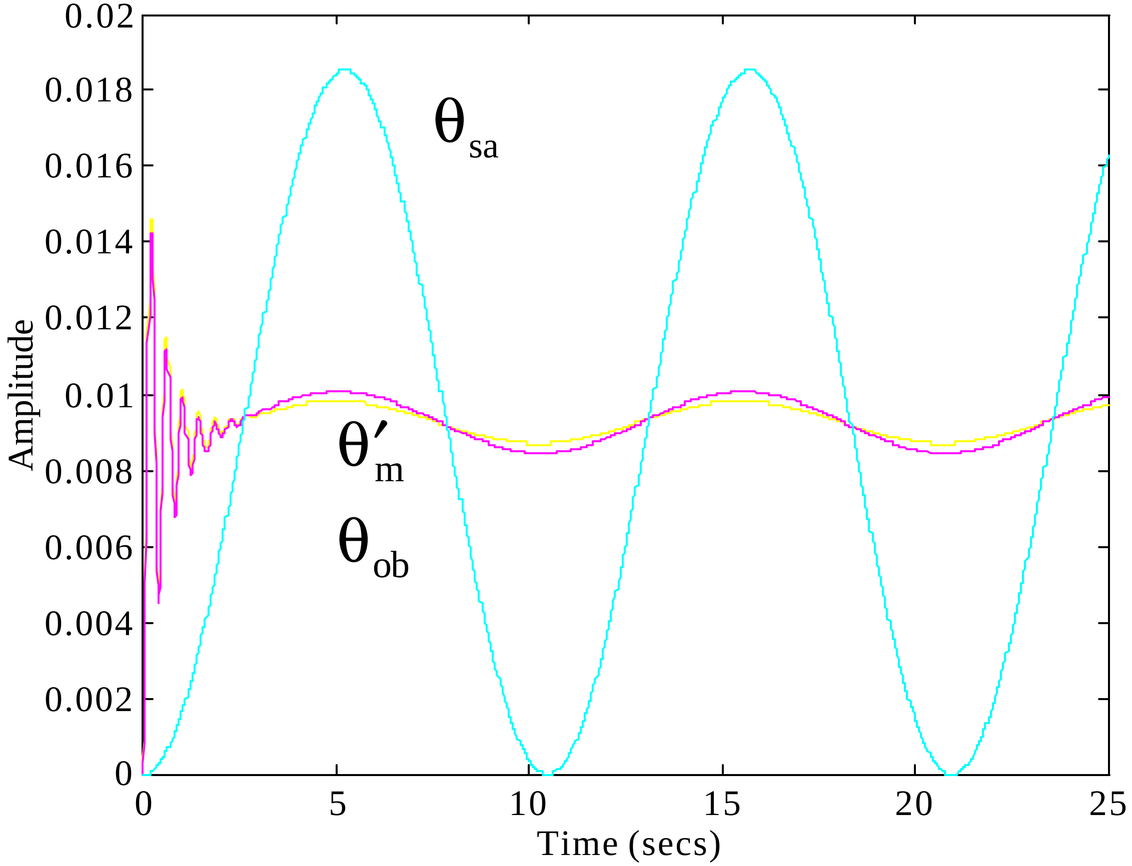
Solar Alpha Rotary Joint Mathematical Model

$$
\begin{bmatrix} \dot{\theta}'_m \\ \dot{\theta}_{ob} \\ \dot{\theta}_{sa} \\ \ddot{\theta}'_m \\ \ddot{\theta}_{ob} \\ \ddot{\theta}_{sa} \end{bmatrix}
=
\begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\frac{-K_1}{N^2 J_m} & \frac{K_1}{N^2 J_m} & 0 & \frac{-B_1}{N^2 J_m} & \frac{B_1}{N^2 J_m} & 0 \\
\frac{K_1}{J_{ob}} & \frac{-K_1 - K_2}{J_{ob}} & \frac{K_2}{J_{ob}} & \frac{B_1}{J_{ob}} & \frac{-B_1 - B_2}{J_{ob}} & \frac{B_2}{J_{ob}} \\
0 & \frac{K_2}{J_{sa}} & \frac{-K_2}{J_{sa}} & 0 & \frac{B_2}{J_{sa}} & \frac{-B_2}{J_{sa}}
\end{bmatrix}
\begin{bmatrix} \theta'_m \\ \theta_{ob} \\ \theta_{sa} \\ \dot{\theta}'_m \\ \dot{\theta}_{ob} \\ \dot{\theta}_{sa} \end{bmatrix}
+
\begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
\frac{NK_t}{N^2 J_m} & 0 \\
0 & 0 \\
0 & \frac{1}{J_{sa}}
\end{bmatrix}
\begin{bmatrix} i_m \\ T_d \end{bmatrix}
$$

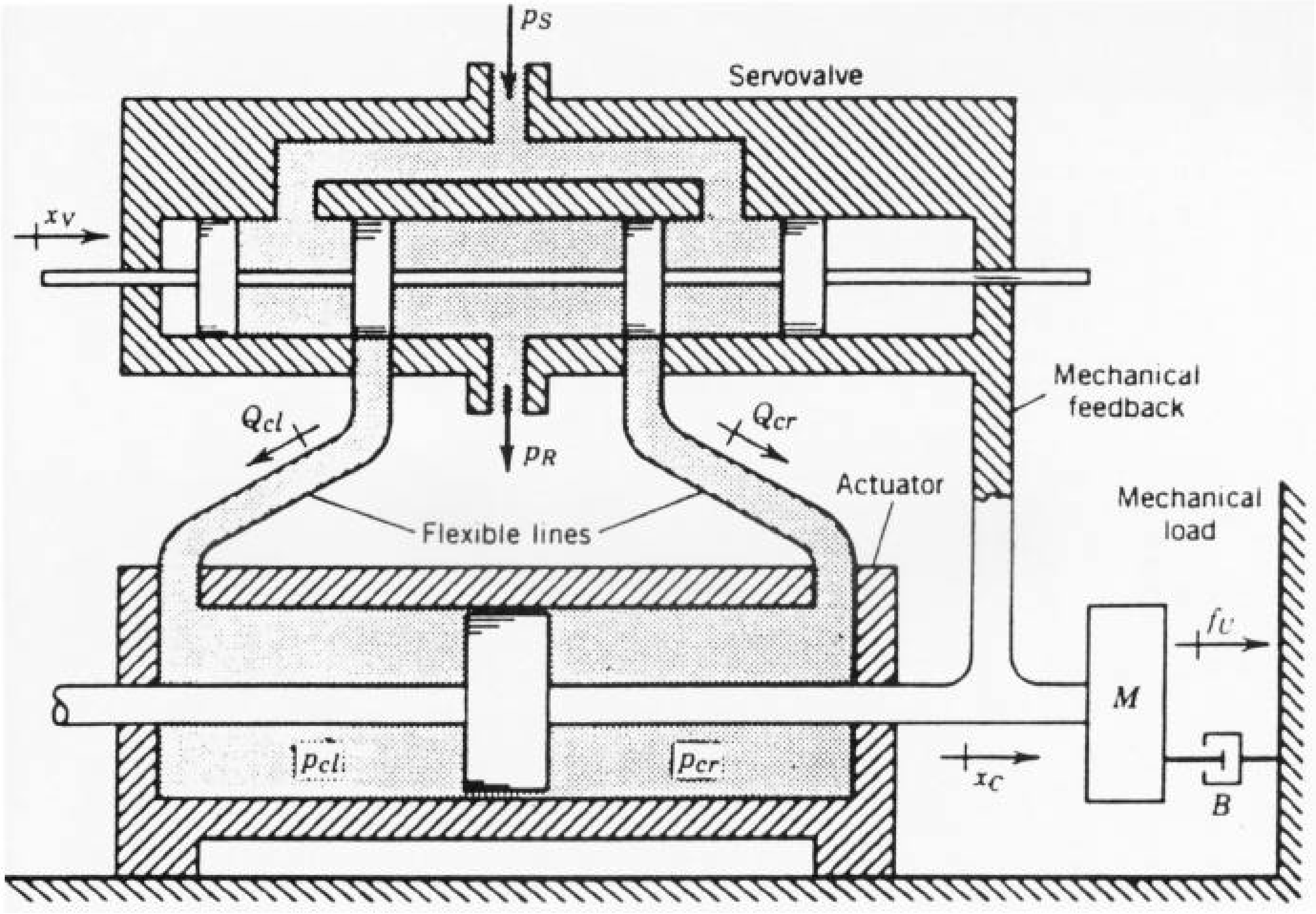
Frequency Response Plots: Input i_m



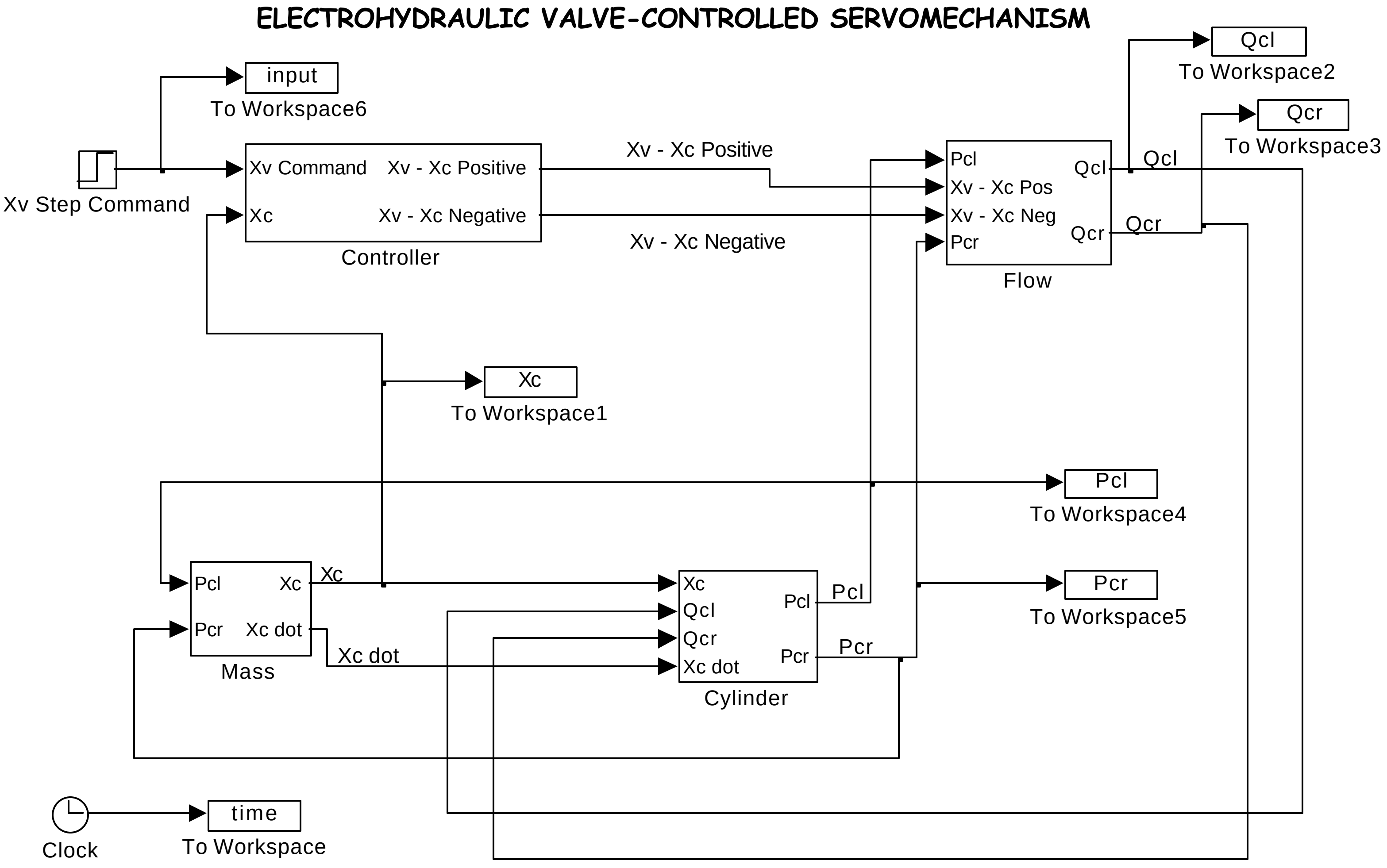
Time Response: $i_m = \cos(0.6t)$



Electrohydraulic Valve-Controlled Servomechanism



Nonlinear Model



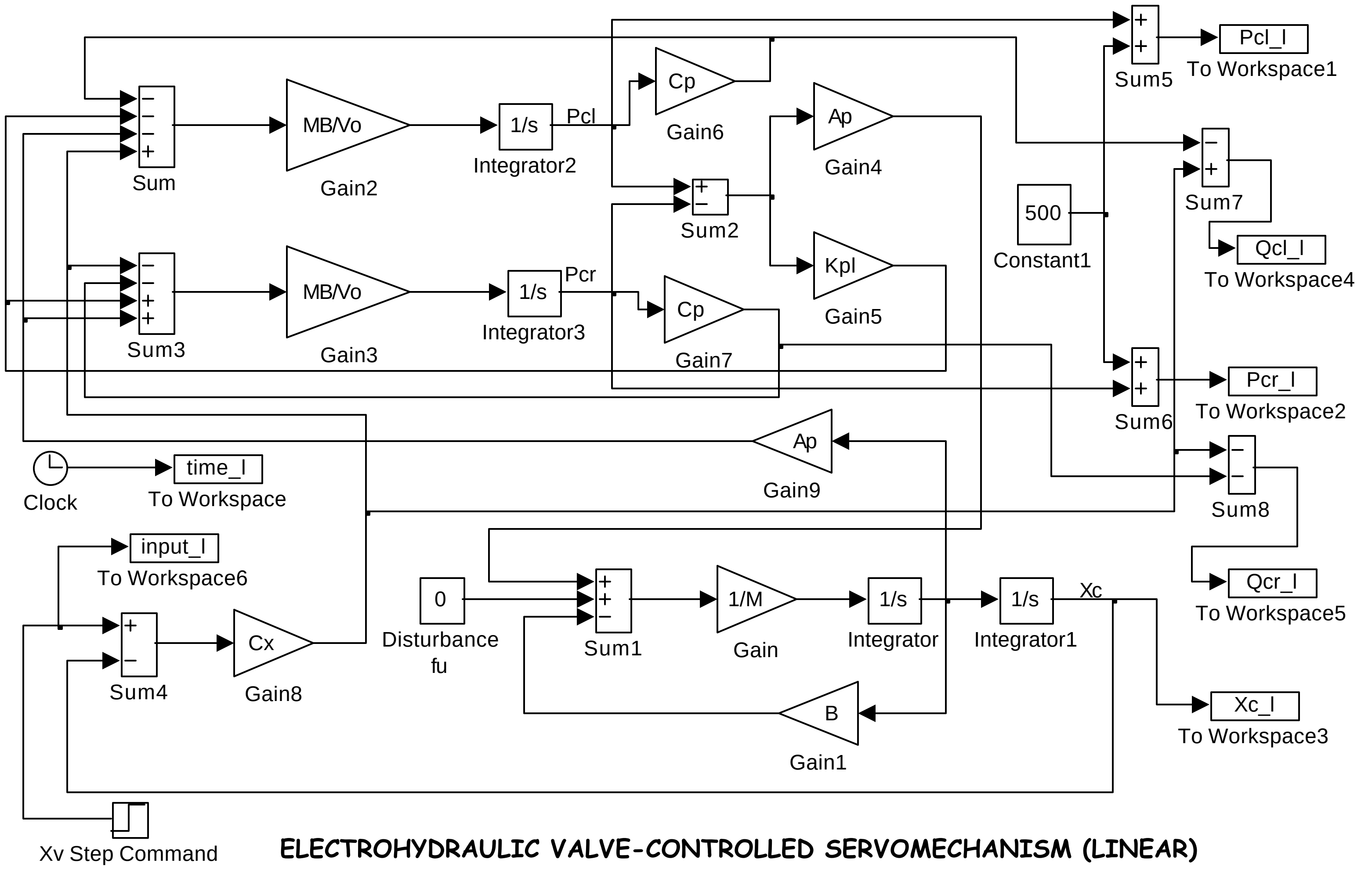
Linear Mathematical Model

$$\left(C_x x_{v,p} - C_p p_{cl,p}\right) - \frac{V_0}{M_B}\frac{dp_{cl,p}}{dt} - K_{pl}\left(p_{cl,p} - p_{cr,p}\right) = A_p \frac{dx_{C,p}}{dt}$$

$$\left(-C_x x_{v,p} - C_p p_{cr,p}\right) - \frac{V_0}{M_B}\frac{dp_{cr,p}}{dt} + K_{pl}\left(p_{cl,p} - p_{cr,p}\right) = -A_p \frac{dx_{C,p}}{dt}$$

$$\left(p_{cl,p} - p_{cr,p}\right)A_p - B\frac{dx_{C,p}}{dt} + f_{U,p} = M\frac{d^2 x_{C,p}}{dt^2}$$

Linear Model



ELECTROHYDRAULIC VALVE-CONTROLLED SERVOMECHANISM (LINEAR)

Take the Laplace Transform of these linear equations and derive six useful transfer functions relating the two inputs, x_v and f_U, to the three outputs, p_{cl}, p_{cr}, and x_C.

$$\begin{bmatrix} \dfrac{V_0 s + M_B\left(K_{pl} + C_p\right)}{C_x M_B} & \dfrac{-K_{pl}}{C_x} & \dfrac{A_p s}{C_x} \\ \dfrac{K_{pl}}{C_x} & \dfrac{-V_0 s - M_B\left(K_{pl} + C_p\right)}{C_x M_B} & \dfrac{A_p s}{C_x} \\ -A_p & A_p & Ms^2 + Bs \end{bmatrix} \begin{bmatrix} p_{cl} \\ p_{cr} \\ x_C \end{bmatrix} = \begin{bmatrix} x_v \\ x_v \\ f_U \end{bmatrix}$$

One of these transfer functions is:

$$\frac{x_C}{x_v}(s) = \frac{K}{s\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1\right)}$$

where

$$K = \frac{2C_x A_p}{2A_p^2 + B(C_p + 2K_{pl})}$$

$$\omega_n = \sqrt{\frac{M_B\left[2A_p^2 + B(C_p + 2K_{pl})\right]}{MV_0}}$$

$$\zeta = \frac{B + \left(\frac{2M_B M}{V_0}\right)K_{pl} + \left(\frac{M_B M}{V_0}\right)C_p}{2\sqrt{\frac{M_B M}{V_0}\left[2A_p^2 + B(C_p + 2K_{pl})\right]}}$$