MEM 255 Introduction to Control Systems
Introduction

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Outline

- **Course practical information**
- **Control: open loop and closed loop**
- **Short history of control**
- **Contemporary applications**
- **Technology drivers**
- **Summary**

What is the course content? What is control? Why should an ME care? Why all the math?

Practical Information

- Lectures: Tues & Thurs 2-3:20 pm
- Comp Lab: Fri only as announced, UG lab will be available at your convenience except when a lab is in session
- URL: http://www.pages.drexel.edu/faculty/hgk22.html
- Text Book: G. F. Franklin, J. D. Powel, and A. Emami-Naeini, Feedback
  Control of Dynamic Systems, 4th ed., Prentice Hall, 2002
- Software: The MathWorks, Inc. The Student Edition of MATLAB, Version 6+Control Toolbox. (15 seats in UG laboratory). Tutorial @ http://www.engin.umich.edu/group/ctm/basic/basic.html

- TA: TBA
- Grading:
  - Homework (3): 10%
  - Midterm (in class): 30%
  - Midterm Project (take home): 30%
  - Final Project (take home): 30%

What you should know going in

- Linear ordinary differential equations,

- Basics of Laplace transform,

- How to model simple mechanical, electrical, fluid and thermal systems.

MEM 255: What you should know going out

- What is a linear system and why do ME's care about them,
- Concepts of state space and transfer function models of a linear system.
- How linear systems behave: input-output dynamics
  - The meaning of poles & zeros
  - The frequency transfer function and Bode Plots
- Block diagram manipulation
- How linear systems behave: state dynamics
  - Eigenvalues & eigenvectors,
  - modal analysis and similarity transformations.
- Stability and Routh table.
- Basic ability to use MATLAB.

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MEM355: What you should know going out

- Understand why automatic control is useful for a mechanical engineer
- Recognize the value of integrated control and process design
- Understand the key concepts of control system design
- Be able to solve simple control problems
- Recognize difficult control problems
- Know relevant mathematical theory
- Have competence in using computational tools

MEM 255: Specific Goals

- Introduce time domain (state space) and transform domain (transfer function) models of linear dynamical systems.
- Develop the general process of deriving state pace models from physical principles.
- Introduce the methods of deriving transfer functions from state space models and vice versa.
- Introduce the basics of transform domain analysis: poles & zeros, the frequency transfer function, Bode Plots and working with block diagrams.
- Introduce the basics of time domain analysis: eigenvalues & eigenvectors, state transition matrix and the "variation of parameters" formula, modal analysis and similarity transformations.
- Develop concept of stability and tools for parametric stability analysis.
- Provide a comprehensive introduction to the control system computations using MATLAB.

MEM 355: Specific Goals

- Define the control system design problem and develop a preliminary appreciation of the tradeoffs involved and requirements for robust stability and performance.
- Develop concepts and tools for ultimate state error analysis.
- Develop the relationship between time domain and frequency domain performance specifications, e.g, rise time, overshoot, settling time, sensitivity function and bandwidth.
- Develop frequency domain design methods, including: the root locus method, Nyquist & Bode methods, and stability margins.
- Provide an introduction to state space design: controllability and observability, pole placement, design via the separation principle (time permitting).
- Emphasize computational methods using MATLAB.

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What is Control?

- Control refers to the manipulation of the inputs to a physical system in order to cause desirable behavior.
    - Cause output variables to track desired values
    - Impose desirable dynamical behavior, e.g., stabilize an unstable system
- Open loop (feedforward) control
    - Exploit knowledge of system behavior to compute necessary inputs
    - Requires accurate model of system
- Closed loop (feedback, active) control
    - Process information from sensors to derive appropriate inputs
    - Allows compensation for model uncertainty, disturbances, noise
    - Alters system dynamics

Open & Closed Loop Control
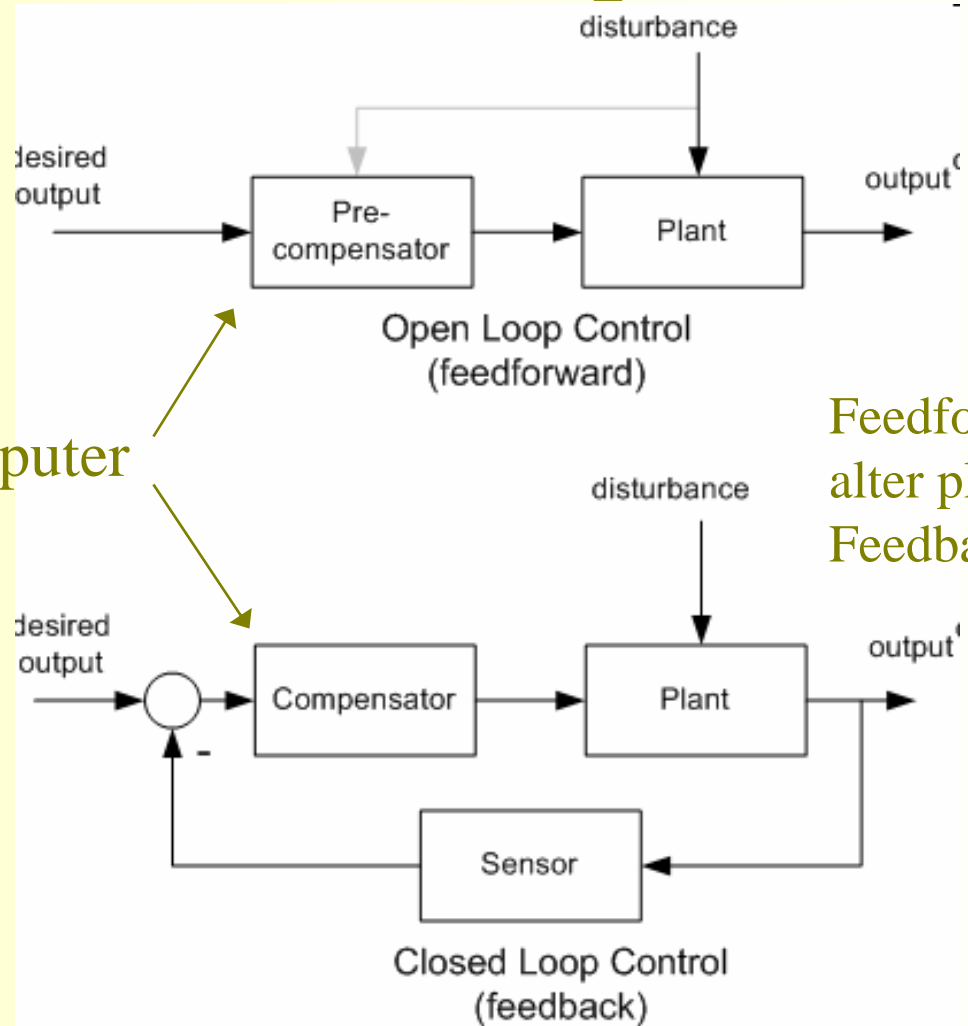
Control computer

Feedforward <u>does not</u> alter plant dynamics. Feedback <u>does</u>.

The Magic of Feedback

- *The adjustment of system inputs based on the observation of its outputs*
- *Feedback is a universal strategy to cope with uncertainty*

In engineering we use feedback:

- To cause a system to behave as desired

- To keep some variables constant

- To stabilize an unstable system

- To reduce effects of disturbances

- To minimize the effect of component variations

- As another alternative for designers

Origins of Control Engineering

Clocks (escapement)	1200-1400
Windmills	1787
Steam Engines (Watt)	1788
Maxwell ~ Governors	1868
Water Turbines	1893
Wright brothers ~ Airplane	1903
Sperry ~ Autopilot (Gyro)	1914
Minorsky ~ Ship steering	1922
Black ~ Feedback amplifier	1928
Ivanoff ~ Temperature regulation	1934
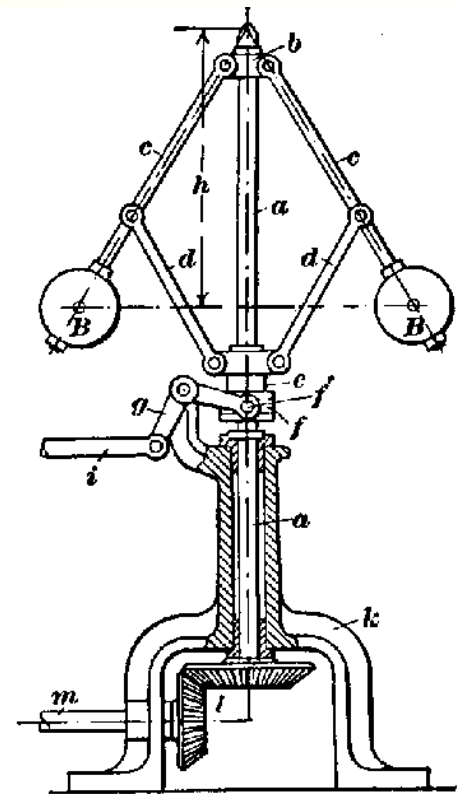
First real control system analysis.
First journal article.
Invention of new control paradigm.

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Wilber Wright 1901

"We know how to construct airplanes. Men also know how to build engines. **The inability to balance and steer still confronts students of the flying problem**. When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance."

Contemporary Applications

Widespread use of automatic control in many fields

- Power generation
- Power transmission
- Process control
- Discrete manufacturing
- Robotics
- Communications
- Automotive
- Buildings
- Aerospace

- Medicine
- Marine Engineering
- Computers
- Instrumentation
- Mechatronics
- Materials
- Physics
- Biology
- Economics

There is a unified framework of theory, design methods and computer tools that cut across fields of application.

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Examples

Mercedes Benz SLR

- Flight control systems
  - Commercial & military "fly-by-wire"
  - Autopilot, auto-landing
  - UAV
- Robotics
  - Precision positioning in manufacturing
  - Remote space/sea environments
  - Minimally-invasive surgery
  - RPV's for surveillance, search and rescue

- Automotive
  - Engine
  - Transmission
  - Cruise, climate control
  - ABS, Traction control, ESP
  - Active suspension
- Power plants
  - Various temps/pressures
  - Power output
  - Emissions control
- Heating, ventilation, air conditioning (HVAC)

Examples, Cont'd

- Materials processing
  - Rapid thermal processing
  - Vapor deposition
- Noise and vibration control
  - Active mounts
  - Speaker systems
- Intelligent vehicle highway systems
  - 'platooning' for high speed, high density travel
  - Automatic merge
  - Obstacle avoidance

- Smart engines
  - Compression systems stall, surge, flutter control
  - Combustion systems lean air/fuel ratio for low emissions, improved efficiency
- Biology/Biomechanics
  - Feedback governs growth, response to stress,
  - Feedback regulates body temperature, blood pressure, and cholesterol level,
  - Feedback makes it possible to stand upright.
  - Feedback enables locomotion.
  - Feedback is pervasive: from the interaction of proteins in cells to the interaction of organisms in complex ecologies.

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Active Control in Automobiles

A typical automobile has 200-300 feedback controllers. Here are a few examples in a contemporary Mercedes.

- Cruise Control
- ABC-active body control
- ABS-anti-lock braking system
- ASR acceleration skid control
- ESP electronic stabilization program
- SBC sensotronic brake control
- BAS brake assist system
- Proximity controlled cruising

Active Body Control

•ABC continuously matches the stiffness and damping characteristics to current driving conditions.

•It is possible, for example, to compensate for the rolling motion of the body when taking a bend in the road.

•Hydraulic cylinders in series with the coil springs, generate forces that counteract wheel load. This is performed with sensors that measure yaw rate, longitudinal and transverse acceleration, vertical acceleration.
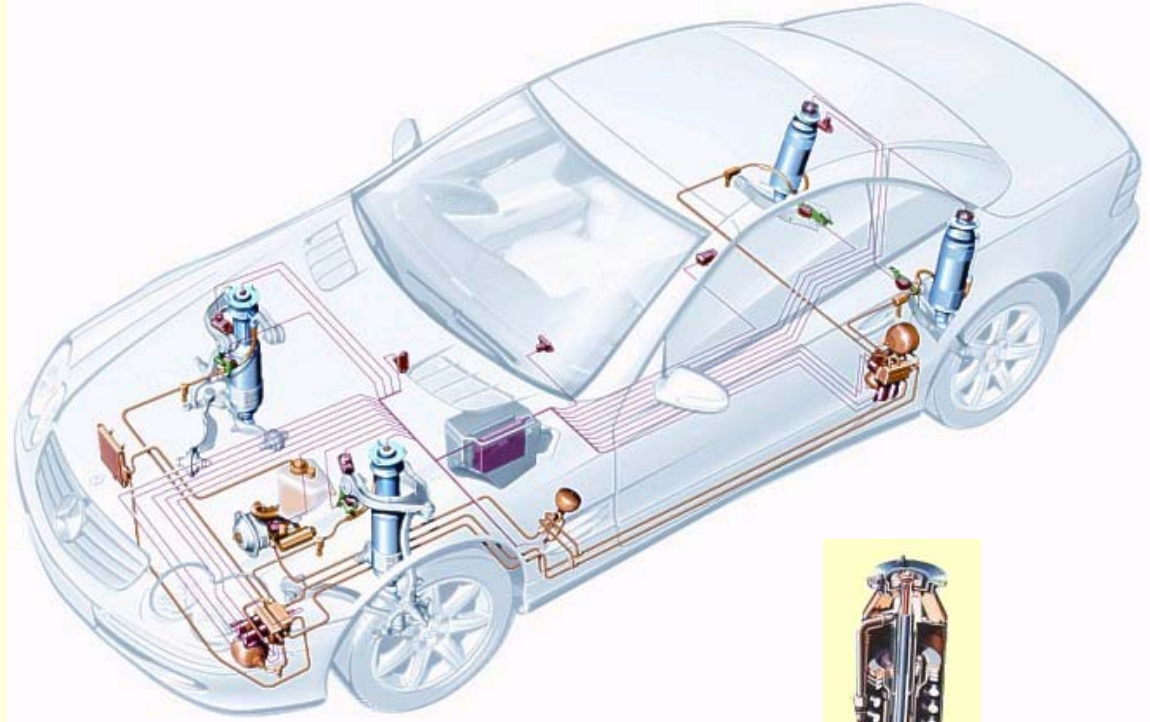
Key Technology Trends

- Computation/microprocessors
  - Cheap and powerful microprocessors opened the door to widespread control applications from 1970's onward
- Sensors and actuators
  - Sensors continue to get smaller, cheaper, faster
  - Macro/micro – scale actuation evolving (power electronics, piezo-electric, EM-rheological fluids)
- Communications and networking
  - Networks replacing point-to-point communication in large systems (e.g., electric power systems) and small (e.g. automotive)

State Space & Transfer Function Models

East Coast Notation
MATLAB

West Coast Notation

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

$$\dot{x} = Fx + Gu$$

$$y = Hx + Ju$$

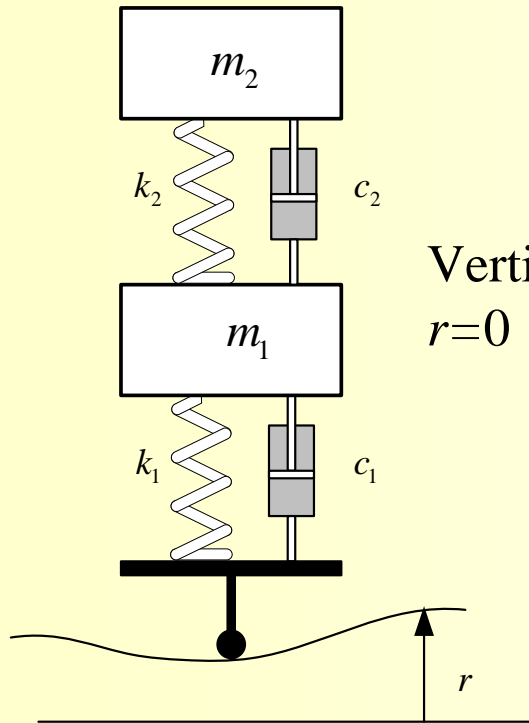State space models are also referred to as time-domain models

$$Y(s) = G(s)U(s),$$

$$Y(s) = L\left[y(t)\right]$$

$$U(s) = L\left[u(t)\right]$$

Transfer Function

Transfer function models are also
Referred to as frequency domain models.

Quarter-Car Suspension

$$m_1 \ddot{x}_1 = -k_2(x_1 - x_2) - k_1(x_1 - r) - c_2(\dot{x}_1 - \dot{x}_2) - c_1(\dot{x}_1 - \dot{r})$$

$$m_2 \ddot{x}_2 = k_2(x_1 - x_2) + c_2(\dot{x}_1 - \dot{x}_2)$$

Vertical motion, x_1, x_2 measured from rest with $r=0$

Using Laplace Transform, derive a relationship between $R(s)$ and $X_2(s)$ (data from Franklin et al)

$$X_2(s) = \frac{(17.333/1.3067)s}{s^4 + 490s^3 + 44067.5s^2 + 157061s + 1.88099} R(s)$$

Quarter-Car State Space Model

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{(k_1+k_2)}{m_1} & -\dfrac{c_1+c_2}{m_1} & \dfrac{k_2}{m_1} & \dfrac{c_2}{m_1} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_2}{m_2} & \dfrac{c_2}{m_2} & -\dfrac{k_2}{m_2} & -\dfrac{c_2}{m_2} \end{bmatrix}\begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix} + \begin{bmatrix} \dfrac{c_1}{m_1} \\ -(c_1+c_2)\dfrac{c_1}{m_1}+\dfrac{k_1}{m_1} \\ 0 \\ \dfrac{c_2 c_1}{m_1} \end{bmatrix} r(t)$$

$$y(t) = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix}$$

Evolution of the Control Discipline

- **Classical control**   **1940**
    - Frequency-domain based tools for linear systems
    - Mainly useful for single-input single-output (SISO) systems
    - WWII years saw 1st application of 'optimal' control
    - Still the main tools used in practice
- **Modern control**   **1960**
    - 'State space' approach for linear systems
    - Useful for SISO and multi-input multi-output (MIMO) systems
    - Relies on linear algebra computations rather than Laplace transform
    - Performance and robustness measures not always explicit
    - Just in time for space exploration
- **Optimal control**   **1970**
    - Find the input that optimizes some objective function (e.g., min fuel, min time)
    - Used for both open loop and closed loop design
- **Robust control**   **1980**
    - Generalizes classical control methods to MIMO case
    - Enabled by modern control development
- **Nonlinear, adaptive, hybrid …**
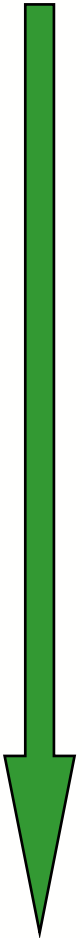
Research Applications in MEM

- Automotive
- Aircraft/Flight Safety
- Power Plants
- Robotics
- Autonomous Vehicles
- Mechatronics
- Biology/Biomechanics
- Electric Power Systems

Summary

- Course content.
- What is a control system?
  - Open loop/closed loop (feedforward/feedback)
- Why is control relevant to ME?
  - Applications! Applications! Applications!
- Why so much math?
  - Abstraction to accommodate many applications in a common framework
  - Explicit design approaches to meet (optimize) specific performance goals.