Lecture 1

- Introduction - Course mechanics
- History
- Control engineering at present

Introduction - Course Mechanics

- What this course is about?
- Prerequisites & course place in the curriculum
- Course mechanics
- Outline and topics
- Your instructor

What this course is about?

- Embedded computing is becoming ubiquitous
- Need to process sensor data and influence physical world. This is control and knowing its main concepts is important.
- Much of control theory is esoteric and difficult
- 90% of the real world applications are based on 10% of the existing control methods and theory
- The course is about these 10%
  - Focus on a few methods used in majority of the applications
  - Some methods are familiar from E105, EE205; actual application of these methods is the key in this course
  - Some material is not covered in other courses

Course Focus and Name

- Academic research
  - Quest for knowledge
  - What else can we say about this topic
  - Mathematical theory
  - Many controls books and papers
- This course
  - Oriented towards engineering practices in industry
  - What is the *minimal* knowledge/skills we need to solve an engineering problem?
  - What *are* the engineering problems?
  - What methods do engineers *actually* use in industry?
  - Additional knowledge sure helps…

Prerequisites and course place

- Prerequisites:
  - Linear algebra: EE263, Math 103
  - Systems and control basics: EE102, ENGR 105, ENGR 205
- Helpful
  - Matlab
  - Modeling and simulation
  - Optimization
  - Application fields
  - Some control theory good, but not assumed.
- Learn more advanced control theory:
  - In ENGR 207, ENGR 209, and ENGR 210
  - Needed for high-performance applications

Course Mechanics

- Descriptive in addition to math and theory. Skills and attitude.
- Grading (the weights are approximate)
  - 35% Homework Assignments (3 at all)
  - 30% Midterm Project
  - 35% Final Project
- Notes at www.stanford.edu/class/ee392M/
  - Posted as available
  - 2003 version available, the 2005 version has less coverage and more depth
- Reference texts
  - *Analysis and Design of Feedback Systems*, Åström and Murray, 2003. http://www.cds.caltech.edu/~murray/courses/cds101/fa03/caltech/am03.html
  - *Feedback Control of Dynamic Systems*, Fourth Edition, Franklin, Powell, Emami-Naeini, Prentice Hall, 2002
  - *Control System Design*, Goodwin, Graebe, Salgado, Prentice Hall, 2001

Outline and topics

Lectures - Mondays & Wednesday
2:30-3:45pm

Assignments - due in a week

Lecture topics

Basic

Lecture 1 Introduction
Lecture 2 Linear Systems
Lecture 3 Basic Feedback
Lecture 4 PID
Lecture 5 Digital Control

SISO Control

Lecture 6 Outer Loop
Lecture 7 SISO Analysis
Lecture 8 SISO Design

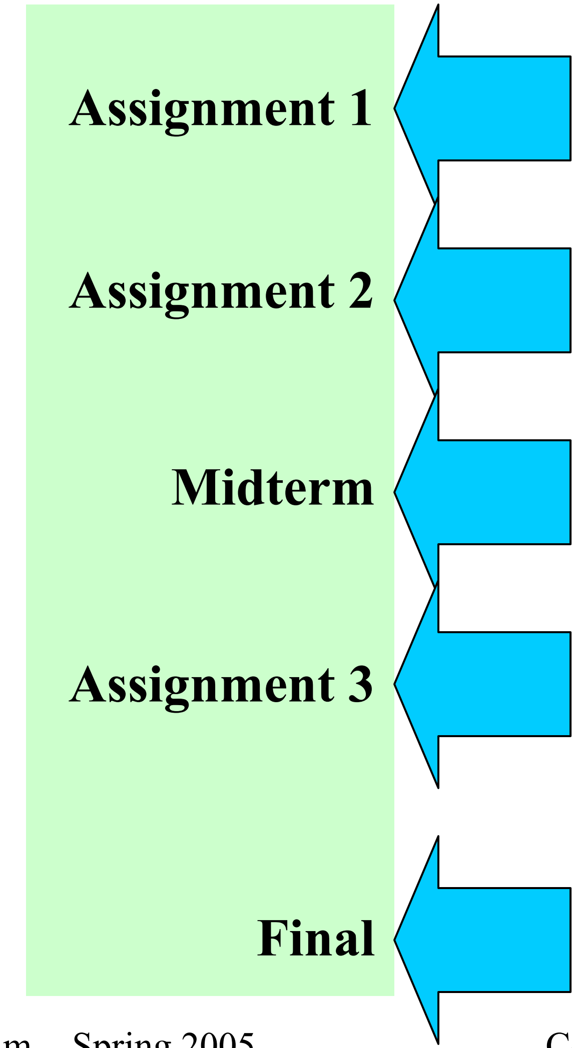
Additional topics

Lecture 9 Modeling & Simulation
Lecture 10 Identification
Lecture 11 Internal Model Control

Advanced Control

Lecture 12 Optimization
Lecture 13 Programmed Control
Lecture 14 Model Predictive Control
Lecture 15 System Health Management

Assignment timeline



Assignment 1

Assignment 2

Midterm

Assignment 3

Final

Lecture 1 Introduction
Lecture 2 Linear Systems
Lecture 3 Basic Feedback
Lecture 4 PID
Lecture 5 Digital Control
Lecture 6 Outer Loop
Lecture 7 SISO Analysis
Lecture 8 SISO Design
Lecture 9 Modeling & Simulation
Lecture 10 Identification
Lecture 11 Internal Model Control
Lecture 12 Optimization
Lecture 13 Programmed Control
Lecture 14 Model Predictive Control
Lecture 15 System Health Management

- Final presentation

Who is your instructor?

- Consulting Professor of EE
- Honeywell Labs
  - Minneapolis, MN
  - San Jose, CA
- Worked on decision and control systems applications across many industries
- PhD from Moscow University
  - Moscow → Munich → Toronto → Vancouver → Palo Alto

Lecture 1 - Control History

- Watt’s governor
- Thermostat
- Feedback Amplifier
- Missile range control
- DCS
- TCP/IP

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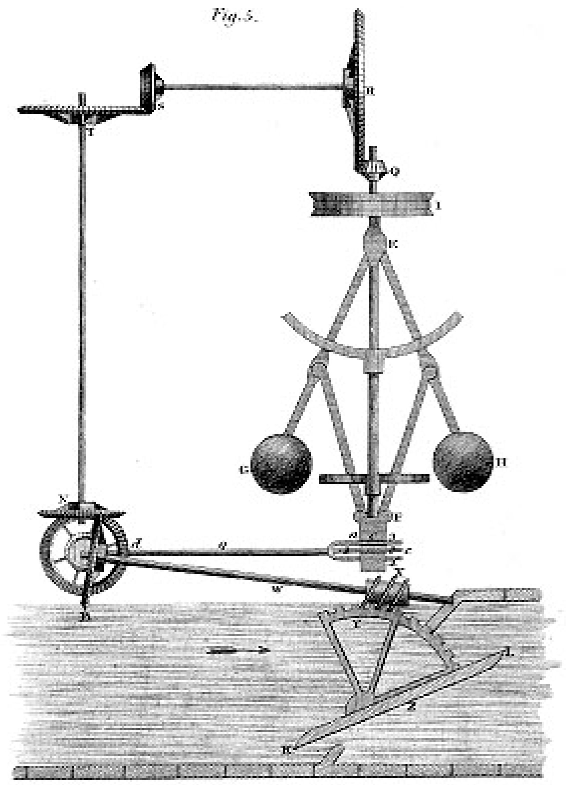
- Current trends
- Control application areas

Why bother about the history?

- Trying to guess, where the trend goes
- Many of the control techniques that are talked about are there for historical reasons mostly. Need to understand that.

1788 Watt’s Flyball Governor

- Watt’s Steam Engine
- Newcomen’s steam engine (1712) was a limited success
- Beginning of systems engineering
- Watt’s systems engineering add-on started the Industrial Revolution
- Analysis of James Clark Maxwell (1868)
- Vyshnegradsky (1877)



From the 1832 *Edinburgh Encyclopaedia*

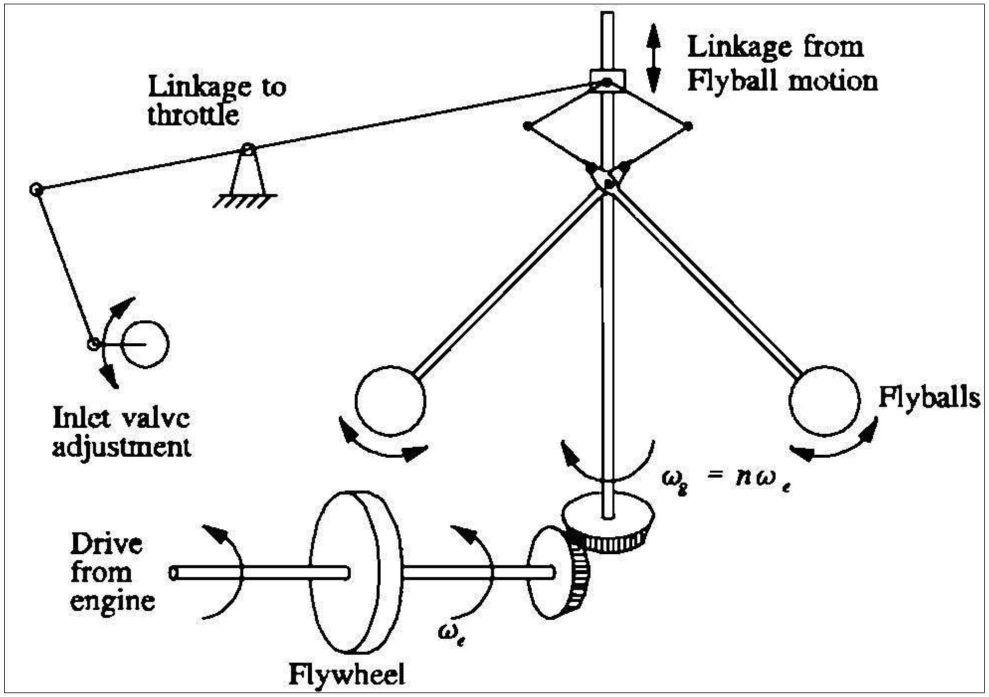
Main Points

- Mechanical technology use was extended from power to regulation
- It worked and improved reliability of steam engines significantly by automating operator’s function
- Analysis was done much later (some 100 years). This seems to be typical!
- Parallel discovery of major theoretical approaches

Watt's governor

- Analysis of James Clark Maxwell (1868)

$$ml\ddot{\phi} = l\left(m\omega_G^2 l\sin\phi\cos\phi - mg\sin\phi - b\dot{\phi}\right)$$



$$J\dot{\omega}_E = k\cos\phi - T_L$$

$$\omega_G = n\omega_E$$

- Linearization

$$\phi = \phi_0 + x \qquad x << 1$$

$$\omega_E = \omega_0 + y \qquad y << 1$$

$$\dddot{y} + a_1\ddot{y} + a_2\dot{y} + a_3 y = 0$$

Watt's governor

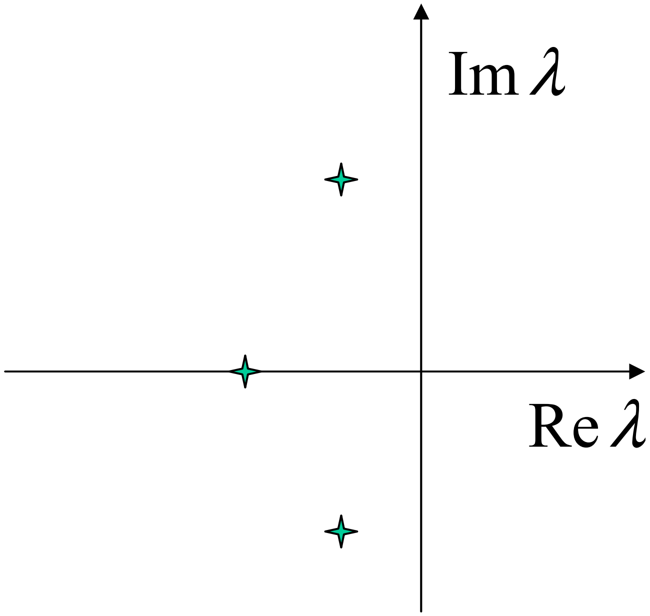
$$\dddot{y} + a_1 \ddot{y} + a_2 \dot{y} + a_3 y = 0$$

Characteristic equation: $y = e^{\lambda t}$

$$\lambda^3 + a_1 \lambda^2 + a_2 \lambda + a_3 = 0$$

Stability condition:

$$\mathrm{Re}\,\lambda_k < 0, \quad (k = 1,2,3)$$



- **Main points:**
  - Modeling
  - P feedback control
  - Linearization
  - LHP poles
- All still valid

1885 Thermostat

- 1885 Al Butz invented damper-flapper
  - bimetal plate (sensor/control)
  - motor to move the furnace damper)
- Started a company that became Honeywell in 1927

1886

Damper Flapper

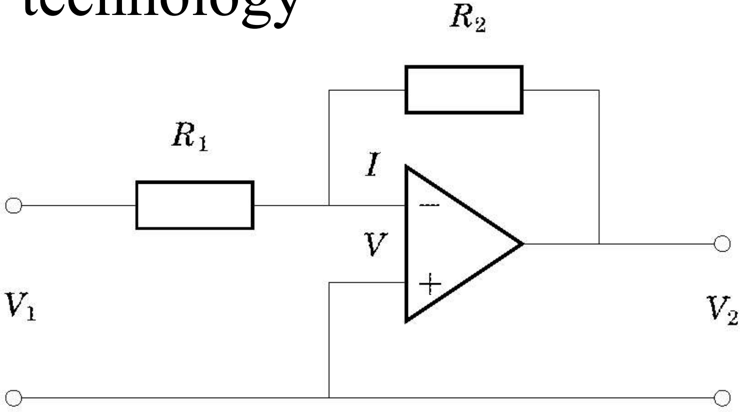
- Thermostat switching on makes the main motor shaft to turn one-half revolution opening the furnace's air damper.
- Thermostat switching off makes the motor to turn another half revolution, closing the damper and damping the fire.
- On-off control based on threshold

Main Points

- Use of emerging electrical system technology
- Significant market for heating regulation (especially in Minnesota and Wisconsin)
- Increased comfort and fuel savings passed to the customer. Customer value proposition
- Integrated control device with an actuator. Add-on device installed with existing heating systems

1930s Feedback Amplifier

- Signal amplification in first telecom systems (telephone)
  Analog vacuum tube amplifier technology
- Feedback concept



$$\frac{V_1 - V}{R_1} = \frac{V - V_2}{R_2}$$

$$V_2 = GV$$

$$\frac{V_1}{V_2} = R_1\left[\frac{1}{R_2} - \frac{1}{G}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right] = -\frac{R_1}{R_2}\left[1 - \frac{1}{G}\left(1 + \frac{R_2}{R_1}\right)\right]$$

- Bode’s analysis of the transients in the amplifiers (1940)

Feedback Amplifier - Main Points

- Electronic systems technology
- Large telecommunications market
- Useful properties of large gain feedback realized: linearization, error insensitivity
- Conceptual step. It was initially unclear why the feedback loop would work dynamically, why it would not always grow unstable.

1940s WWII Military Applications

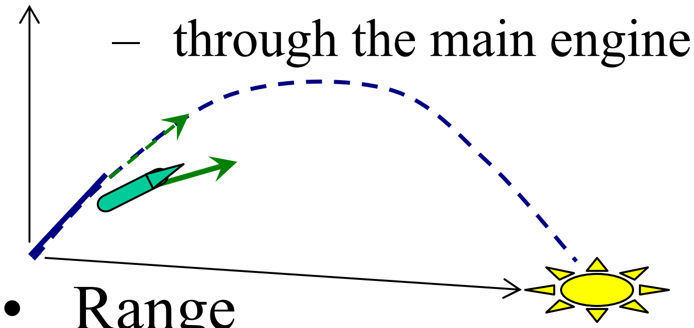
- Sperry Gyroscope Company – flight instruments – later bought by Honeywell to become Honeywell aerospace control business.
- Servosystem – gun pointing, ship steering, using gyro
- Norden bombsight – Honeywell C-1 autopilot - over 110,000 manufactured.
- Concepts – electromechanical feedback, PID control.
- Nyquist, servomechanism, transfer function analysis,

Autopilot - Main Points

- Enabled by the navigation technology - Sperry gyro
- Honeywell got the autopilot contract because of its control system expertise – in thermostats
- Emergence of cross-application control engineering technology and control business specialization.

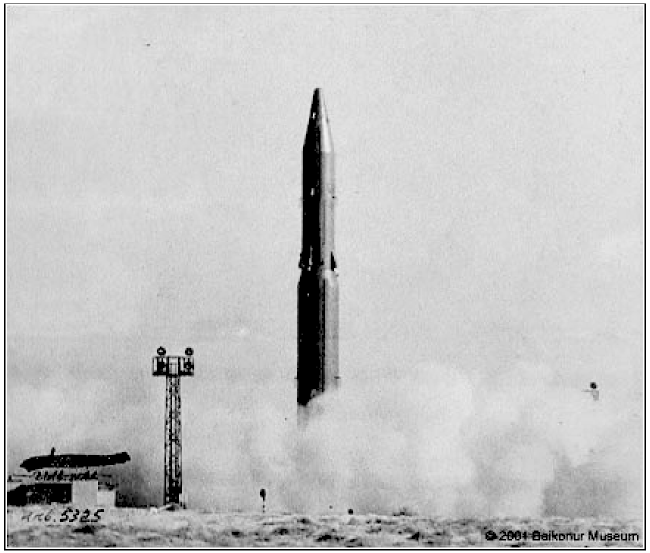
1960s - Rocket science

- SS-7 missile range control
  - through the main engine cutoff time.



- Range

$$r = F\left(\Delta V_x, \Delta V_y, \Delta X, \Delta Y\right)$$



USSR R-16/8K64/SS-7/Saddler
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http://www.russianspaceweb.com/r16.html

- Range Error

$$\delta r(t) = f_1 \Delta V_x(t) + f_2 \Delta V_y(t) + f_3 \Delta X(t) + f_4 \Delta Y(t)$$

- Algorithm:
  - track $\delta r(t)$, cut the engine off at T when $\delta r(T) = 0$

Missile range control - Main Points

- Nominal trajectory needs to be pre-computed and optimized
- Need to have an accurate inertial navigation system to estimate the speed and coordinates
- Need to have feedback control that keeps the missile close to the nominal trajectory (guidance and flight control system)
- $f_1,\ f_2,\ f_3,\ f_4,$ and f_T must be pre-computed
- Need to have an on-board device continuously computing

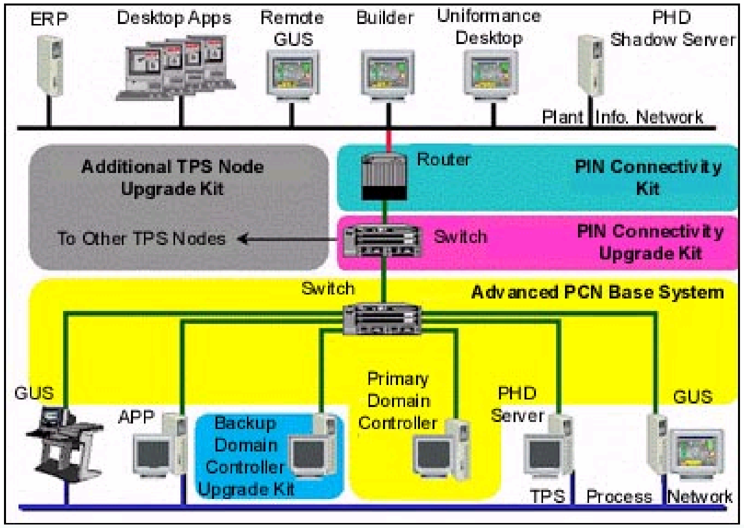
$$\delta r(t) = f_1 \Delta V_x(t) + f_2 \Delta V_y(t) + f_3 \Delta X(t) + f_4 \Delta Y(t)$$

1975 - Distributed Control System

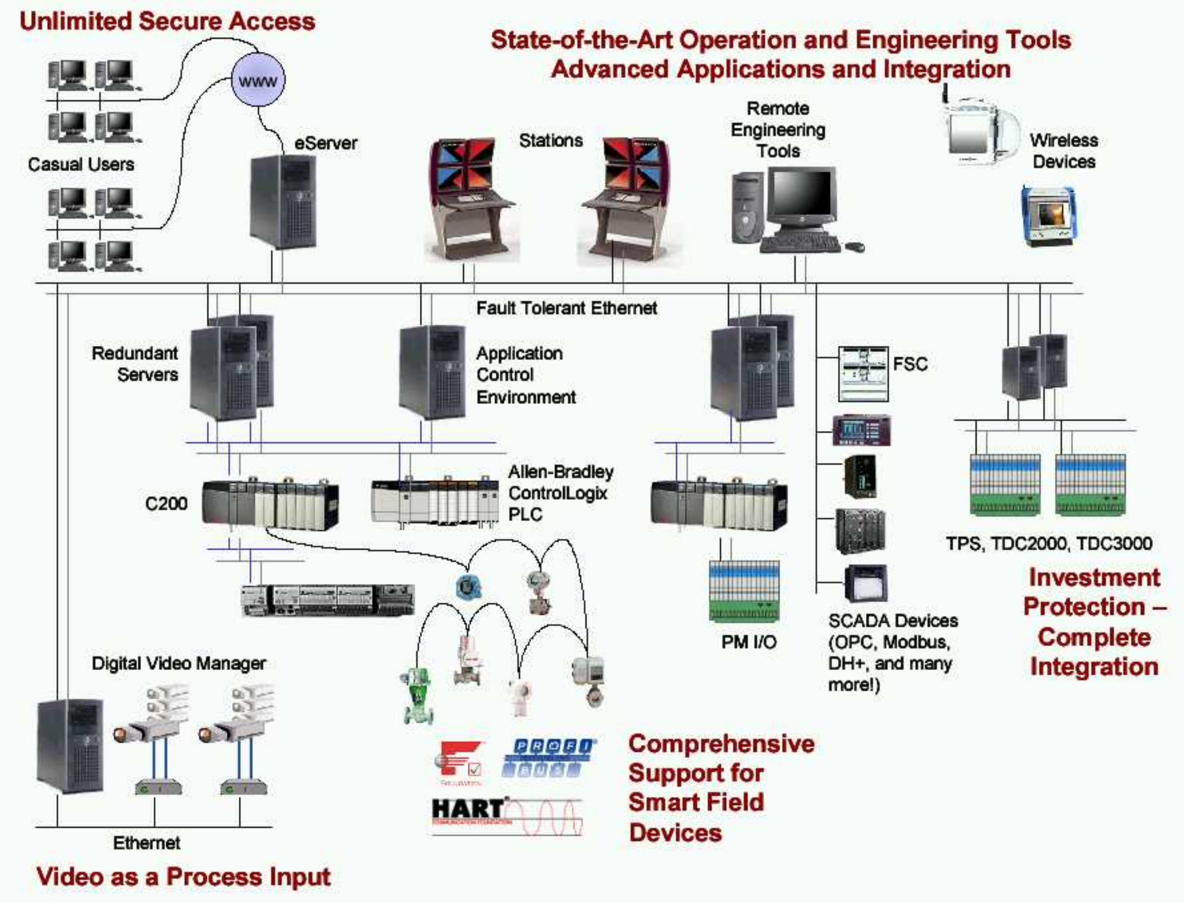
- 1963 - Direct digital control was introduced at a petrochemical plant (Texaco)
- 1970 - PLC's were introduced on the market.
- 1975 - First DCS was introduced by Honeywell
- PID control, flexible software
- Networked control system, configuration tuning and access from one UI station
- Auto-tuning technology

DCS example

Honeywell Experion PKS



Honeywell Plantscape

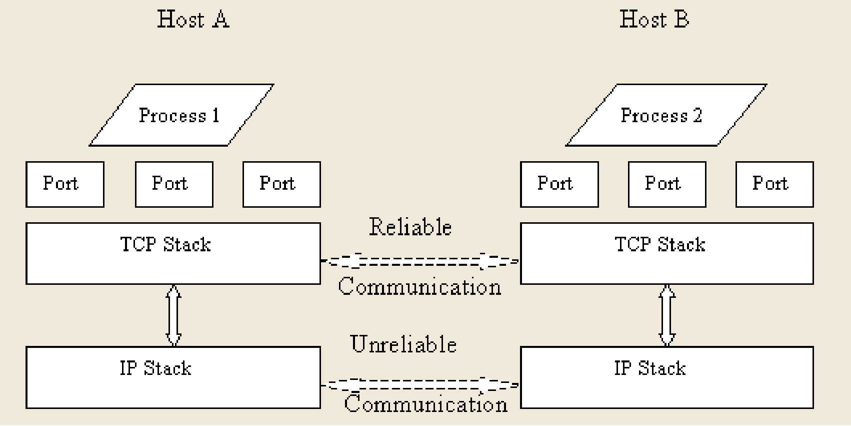


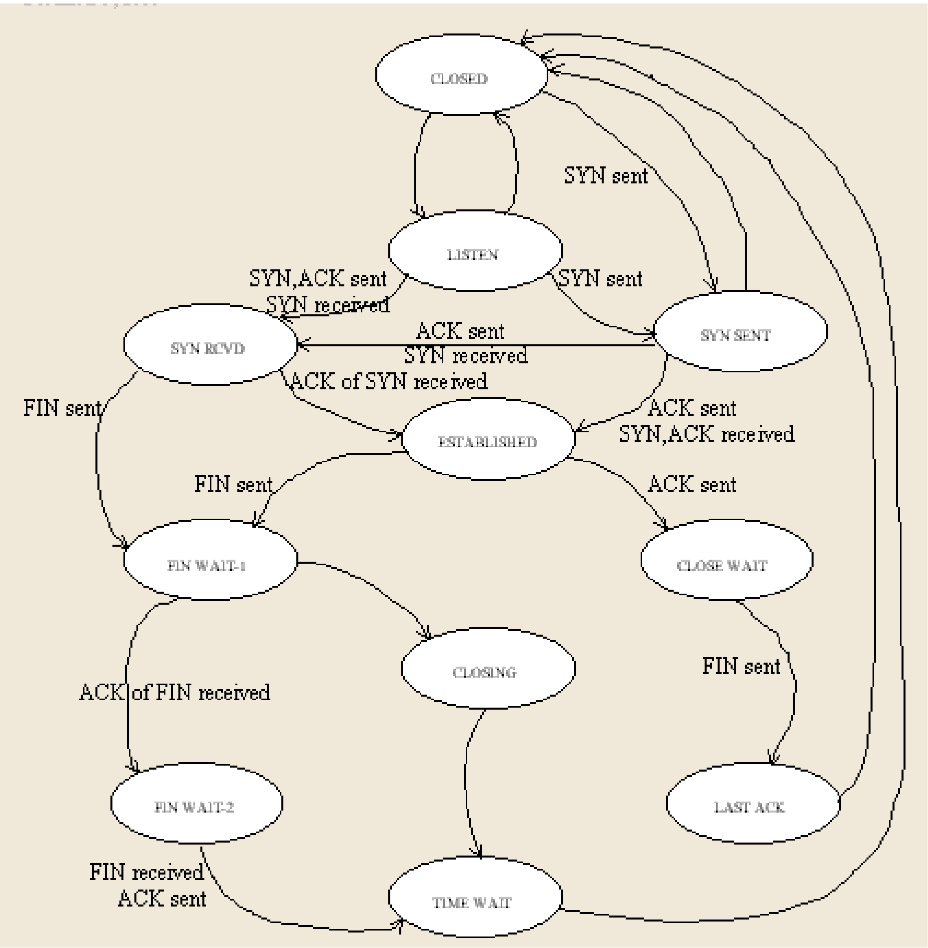
on

DCS - Main Points

- Digital technology + networking
- Rapid pace of the process industry automation
- The same PID control algorithms
- Deployment, support and maintenance cost reduction for massive amount of loops
- Auto-tuning technology
- Industrial digital control is becoming a commodity
- Facilitates deployment of supervisory control and monitoring

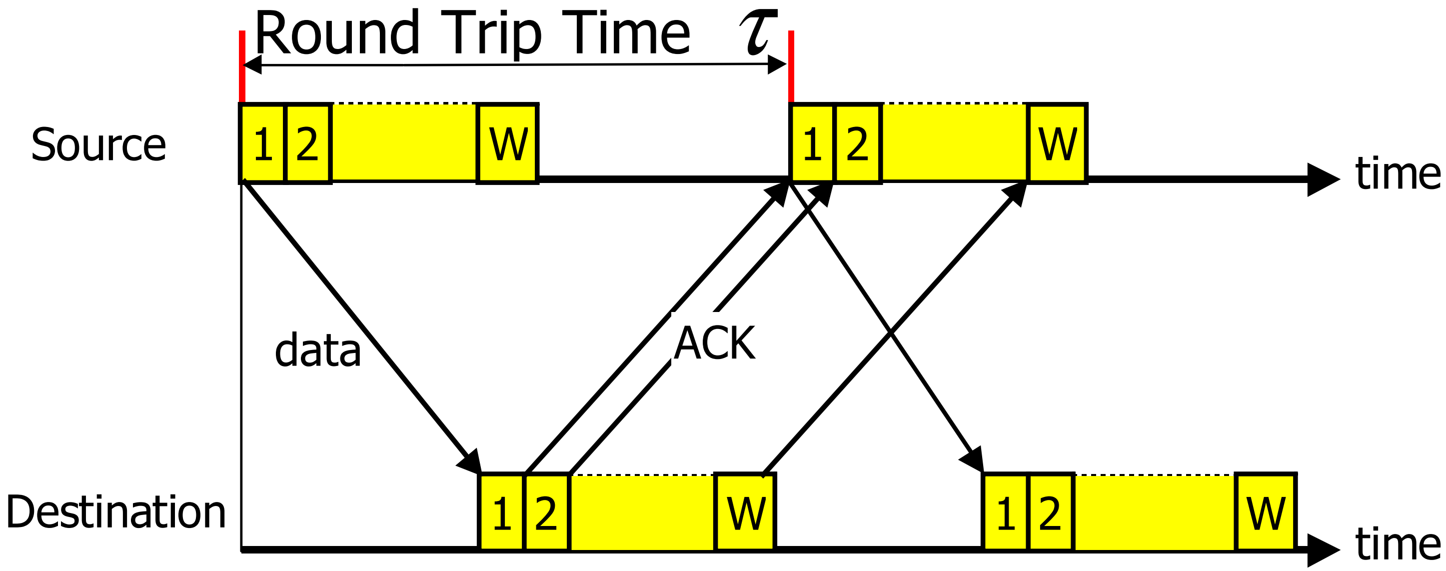
1974 - TCP/IP





- TCP/IP - Cerf/Kahn, 1974
- Berkeley-LLNL network crash, 1984
- Congestion control -Van Jacobson, 1986

TCP flow control



Transmission rate: $x = \dfrac{W}{\tau}$ packets/sec

Here:

- Flow control dynamics near the maximal transmission rate
- From S.Low, F.Paganini, J.Doyle, CSM, 2000

TCP Reno congestion avoidance

```
for every loss {
      W = W/2
      }
for every ACK {
      W += 1/W
      }
```

- packet acknowledgment rate: *x*
- lost packets: with probability *q*

$$\Delta x_{lost} = -xW/2$$

- transmitted: with probability (1-*q*)

$$\Delta x_{sent} = x/W$$

$$\dot{x} = q\frac{\Delta x_{lost}}{\tau} + (1-q)\frac{\Delta x_{sent}}{\tau} \qquad x = \frac{W}{\tau}$$

$$\dot{x} = \frac{1-q}{\tau^2} - \frac{1}{2}qx^2$$

- x - transmission rate
- τ - round trip time
- q - loss probability

TCP flow control - Main Points

- Flow control enables stable operation of the Internet
- Developed by CS folks - no ‘controls’ analysis
- Ubiquitous, TCP stack is on ‘every’ piece of silicon
- Analysis and systematic design is being developed some 20 years later
- The behavior of the network is important. We looked at a single transmission link.
- Most of analysis and systematic design activity are happening in the last 5-6 years and this is not over yet ...

Past → Present

- That was history
- What is going on in control at present?

Control Engineering at Present

Controls people could ask:

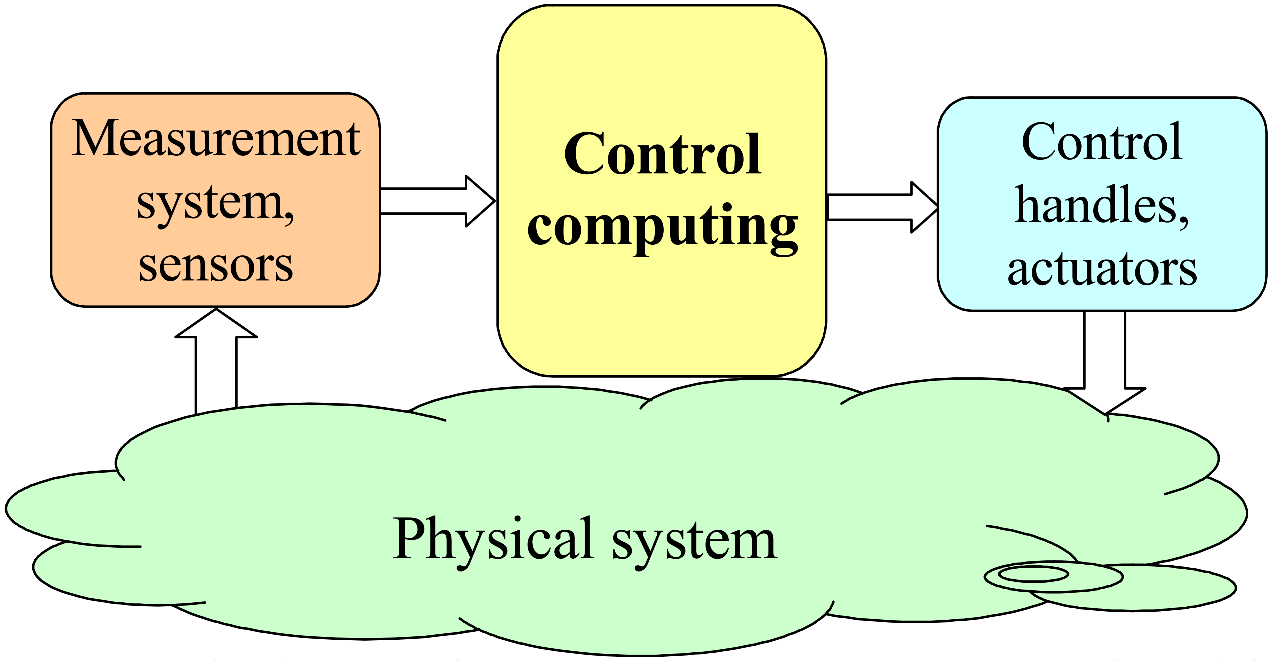
- What big control application is coming next?
- Where and how control technology will be used?

Other engineers could ask:

- What do we need to know about controls to get by?

Will discuss in this course, along with some systems engineering ideas

Focus of This Course



Measurement system, sensors

Control computing

Control handles, actuators

Physical system

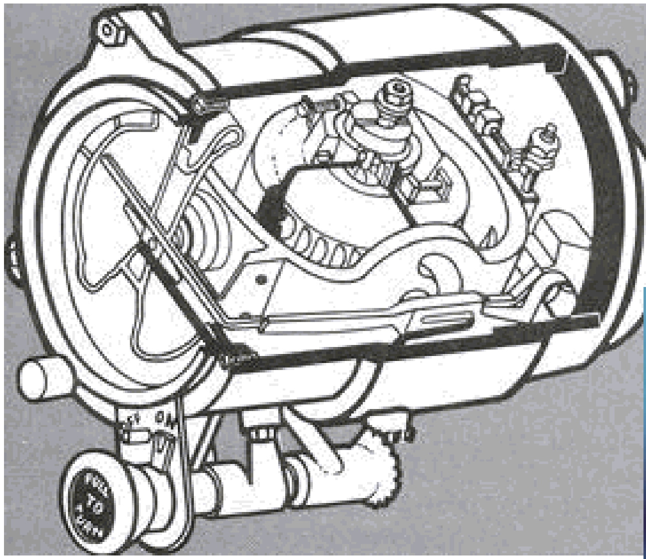
- This course is focused on **control computing** algorithms and their relationship with the overall system design.
- System engineering (design and analysis) is closely related to control computing analysis

Technology Trends

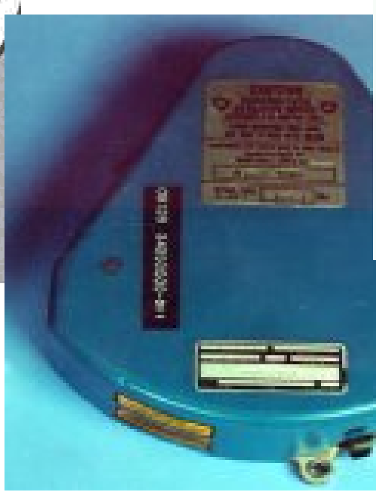
- Why this is relevant and important at present?
- Computing is becoming ubiquitous
- Sensors are becoming miniaturized, cheap, and pervasive. MEMS sensors
- Actuator technology developments include:
  - evolution of existing types
  - previously hidden in the system, not actively controlled
  - micro-actuators (piezo, MEMS)
  - control handles other than mechanical actuators, e.g., in telecom

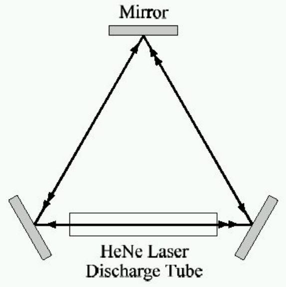
Measurement system evolution.

Navigation system example

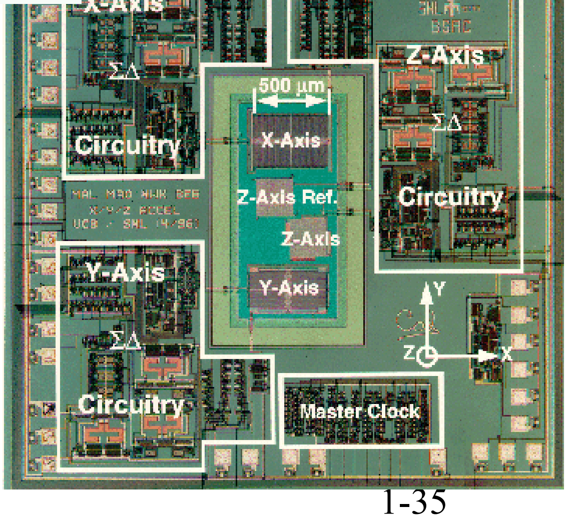


•Mechanical gyro by Sperry – for ships, aircraft. Honeywell acquired Sperry Aerospace in 1986 - avionics, space.





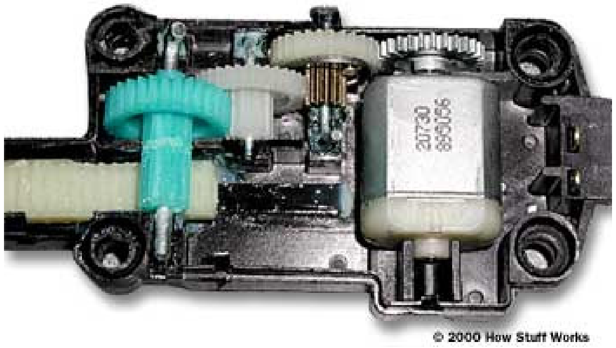
- Laser ring gyro, used in aerospace presently.



- MEMS gyro – good for any vehicle/mobile appliance.
  - (1") ^{3} integrated navigation unit

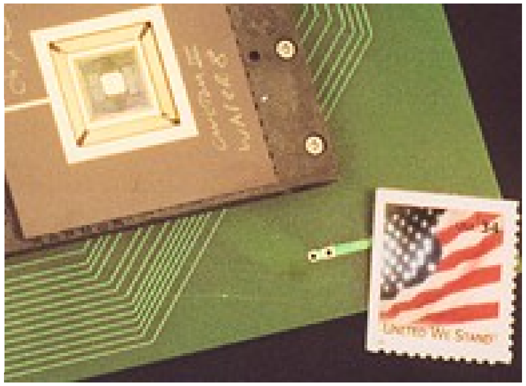
Actuator evolution

- Electromechanical actuators: car power everything

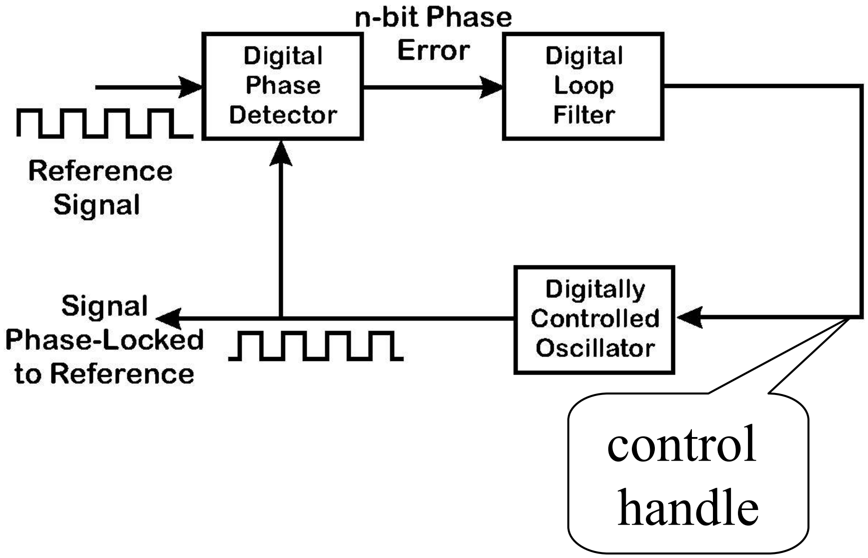


- Adaptive optics, MEMS


µDM 140, 3.3 mm



- Communication - digital PLL


n-bit Phase Error
Digital Phase Detector
Digital Loop Filter
Reference Signal
Signal Phase-Locked to Reference
Digitally Controlled Oscillator
control handle

Control computing

- Computing grows much faster than the sensors and actuators
- CAD tools, such as Matlab/Simulink, allow focusing on algorithm design. Implementation is automated
- Past: control was done by dedicated and highly specialized experts. Still the case for some very advanced systems in aerospace, military, automotive, etc.
- Present: control and signal-processing technology are standard technologies associated with computing.
- Embedded systems are often designed by system/software engineers.
- This course emphasizes practically important issues of control computing

Control and Systems Engineering

- Computing element - software
- System, actuator, and sensor physics might be very different
- Modeling abstraction
- Controls and systems engineering are used across many applications
  - similar principles
  - transferable skills
  - mind the application!

Practical Issues of Control Design

- Technical requirements
- Economics: value added, # of replications
  - automotive, telecom, disk drives - millions of copies produced
  - space, aviation - unique to dozens to several hundreds
  - process control - each process is unique, hundreds of the same type
- Developer interests, cool factor
- Integration with existing system features
- Skill set in engineering development and support
- Field service/support requirements
- Marketing/competition, creation of unique IP
- Regulation/certification: FAA/FDA

Major control applications

Specialized control groups, formal development processes

- Aviation
  - Guidance, Navigation, and Control (GN&C)
  - propulsion - engines
  - vehicle utilities: power, environmental control, etc
- Automotive
  - powertrain
  - suspension, traction, braking, steering
- Disk drives
- Industrial automation and process control
  - process industries: refineries, pulp and paper, chemical
  - semiconductor manufacturing processes
  - home and buildings

Commercial applications

Advanced design - commercial

- Embedded mechanical
  - mechatronics/servo actuators
- Robotics
  - lab automation
  - manufacturing plant robots (e.g., automotive)
  - semiconductors
- Power
  - generation and transmission
- Transportation
  - locomotives, elevators
  - marine
- Nuclear engineering

High-performance applications

Advanced design

- Aerospace and Defense
  - aero, ground, space vehicles - piloted and unmanned
  - missiles/munitions
  - comm and radar: ground, aero, space
  - campaign control: C4ISR
  - directed energy
- Science instruments
  - astronomy
  - accelerators
  - fusion: TOKAMAKs, LLNL ignition

Embedded applications

No specialized control groups

- Embedded controllers
  - consumer
  - test and measurement
  - power/current
  - thermal control
- Telecom
  - PLLs, equalizers
  - antennas, wireless, las comm
  - flow/congestion control
  - optical networks - analog, physics

Emerging control applications

A few selected cases

- Biomedical
    - life support: pacemakers anesthesia
    - diagnostics: MRI scanners, etc
    - ophthalmology
    - bio-informatics equipment
    - robotics surgery
- Computing
    - task/load balancing
- Finance and economics
    - trading