Lecture 1

- Introduction - Course mechanics
- History
- Modern control engineering

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%

Prerequisites and course place

- Prerequisites:
  - Linear algebra: EE263, Math 103
  - Systems and control: 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

Course Mechanics

- Descriptive in addition to math and theory
- Grading
  - 25% Homework Assignments (4 at all)
  - 35% Midterm Project
  - 40% Final Project
- Notes at www.stanford.edu/class/ee392M/
- Reference texts
  - *Control System Design*, Astrom, posted as PDF
  - *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 & Fridays

Assignments - Fridays, due on Friday

Lecture topics

Basic

1. Introduction and history
2. Modeling and simulation
3. Control engineering problems
4. PID control
5. Feedforward
6. SISO loop analysis
7. SISO system design

Advanced

8. Model identification
9. Processes with deadtime, IMC
10. Controller tuning
11. Multivariable control - optimization
12. Multivariable optimal program
13. MPC - receding horizon control

Breadth

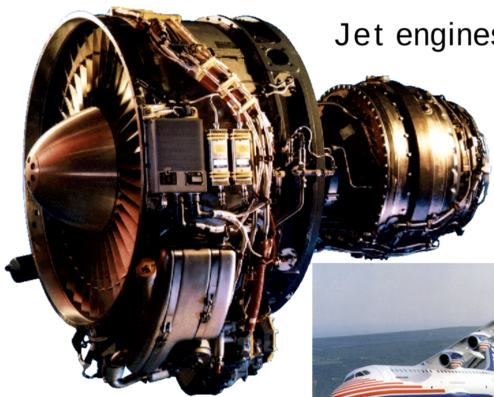
14. Handling nonlinearity
15. System health management
16. Overview of advanced topics

Who is your instructor?

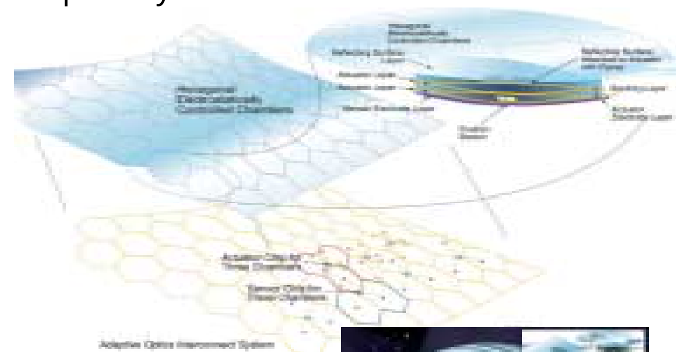
- Dimitry Gorinevsky
- Consulting faculty (EE)
- Honeywell Labs
  - Minneapolis
  - Cupertino
- Control applications across many industries
- PhD from Moscow University
  - Moscow → Munich → Toronto → Vancouver → Palo Alto

Some stuff I worked on

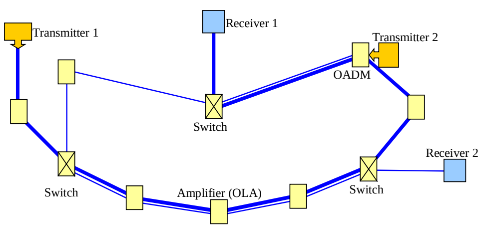
Jet engines



Space systems



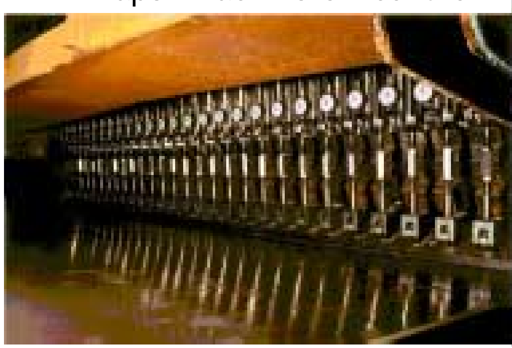
WDM networks

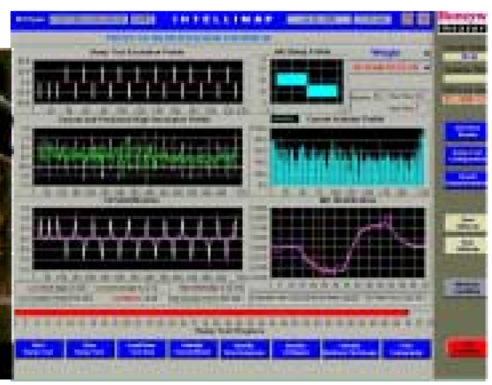


Powertrain control

Walking machine

Paper machine CD control





Lecture 1 - Control History

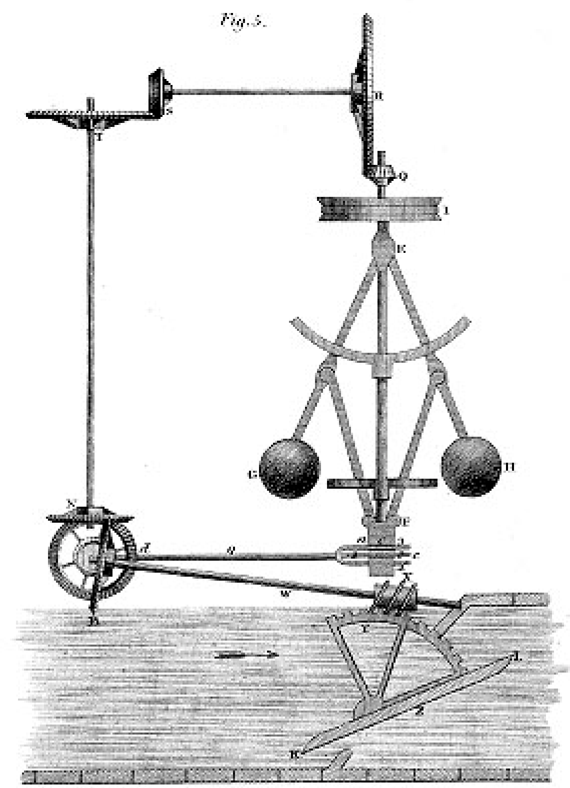
- Watt's governor
- Thermostat
- Feedback Amplifier
- Missile range control
- TCP/IP
- DCS

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) had 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*

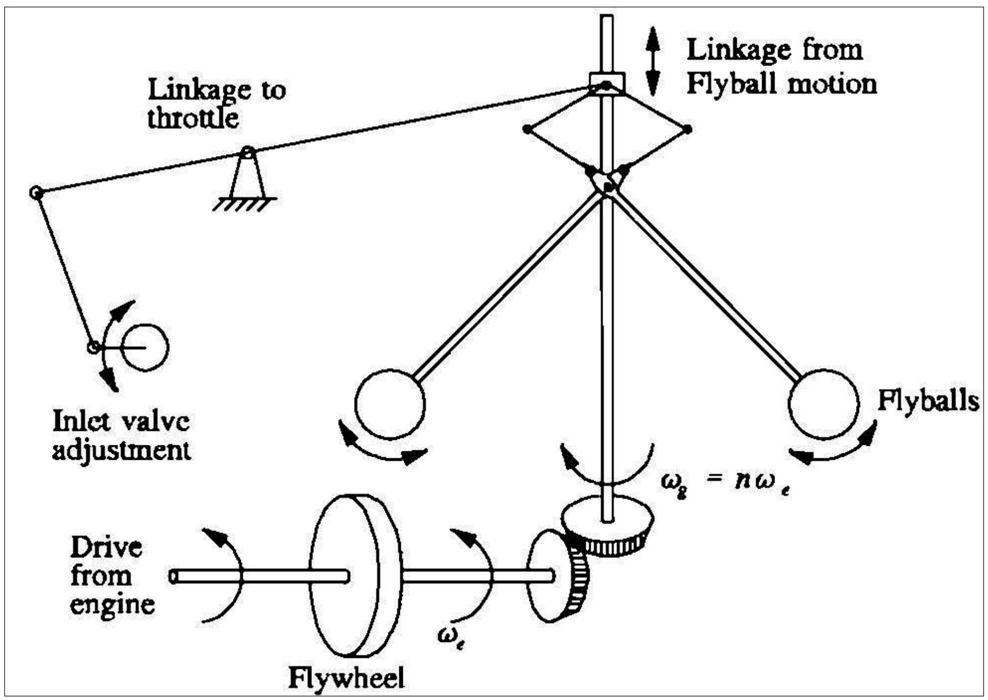
Rubs

- 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 is 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

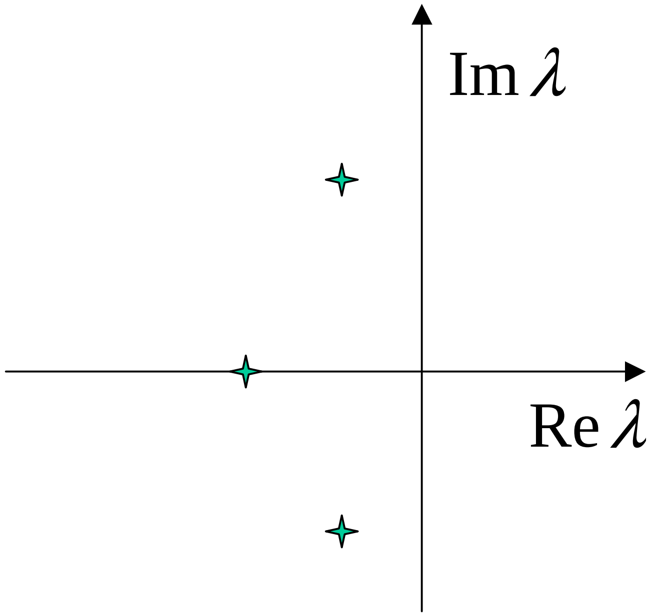
$$\dddot{y} + a_1\ddot{y} + a_2\dot{y} + a_3 y = 0$$

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

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

Stability condition:

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



- Gist:
  - Model; 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

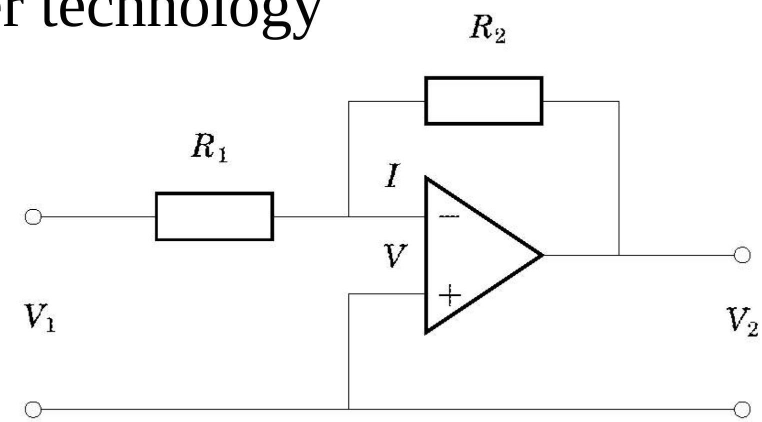
- Thermostat switching on makes the main motor shaft to turn one-half revolution opening the furnace's air damper.
- Thermostat switching off makes the motor to turn another half revolution, closing the damper and damping the fire.
- On-off control based on threshold

Rubs

- 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 - Rubs

- Electronic systems technology
- Large communication 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 would it not grow unstable.

1940s WWII Military Applications

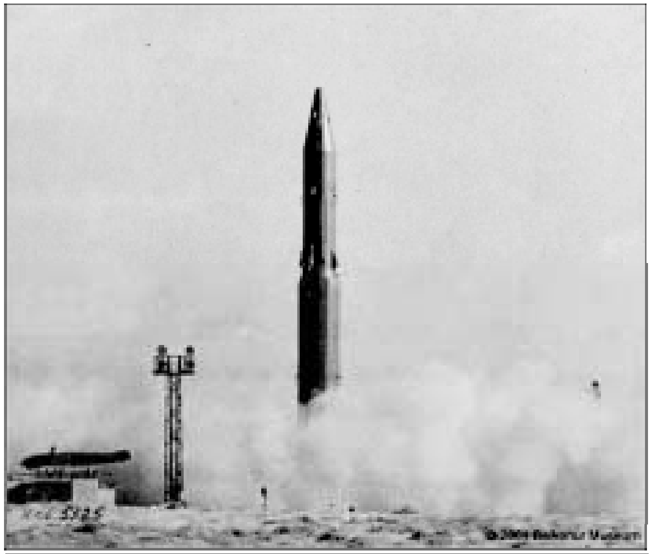
- Sperry Gyroscope Company – flight instruments – later bought by Honeywell to become Honeywell aerospace control business.
- Servosystem – gun pointing, ship steering, using gyro
- Norden bombsight – Honeywell C-1 autopilot - over 110,000 manufactured.
- Concepts – electromechanical feedback, PID control.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

Autopilot - Rubs

- 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.



USSR R-16/8K64/SS-7/Saddler

http://www.russianspaceweb.com/r16.html

- Range

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

- 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 - Rubs

- 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

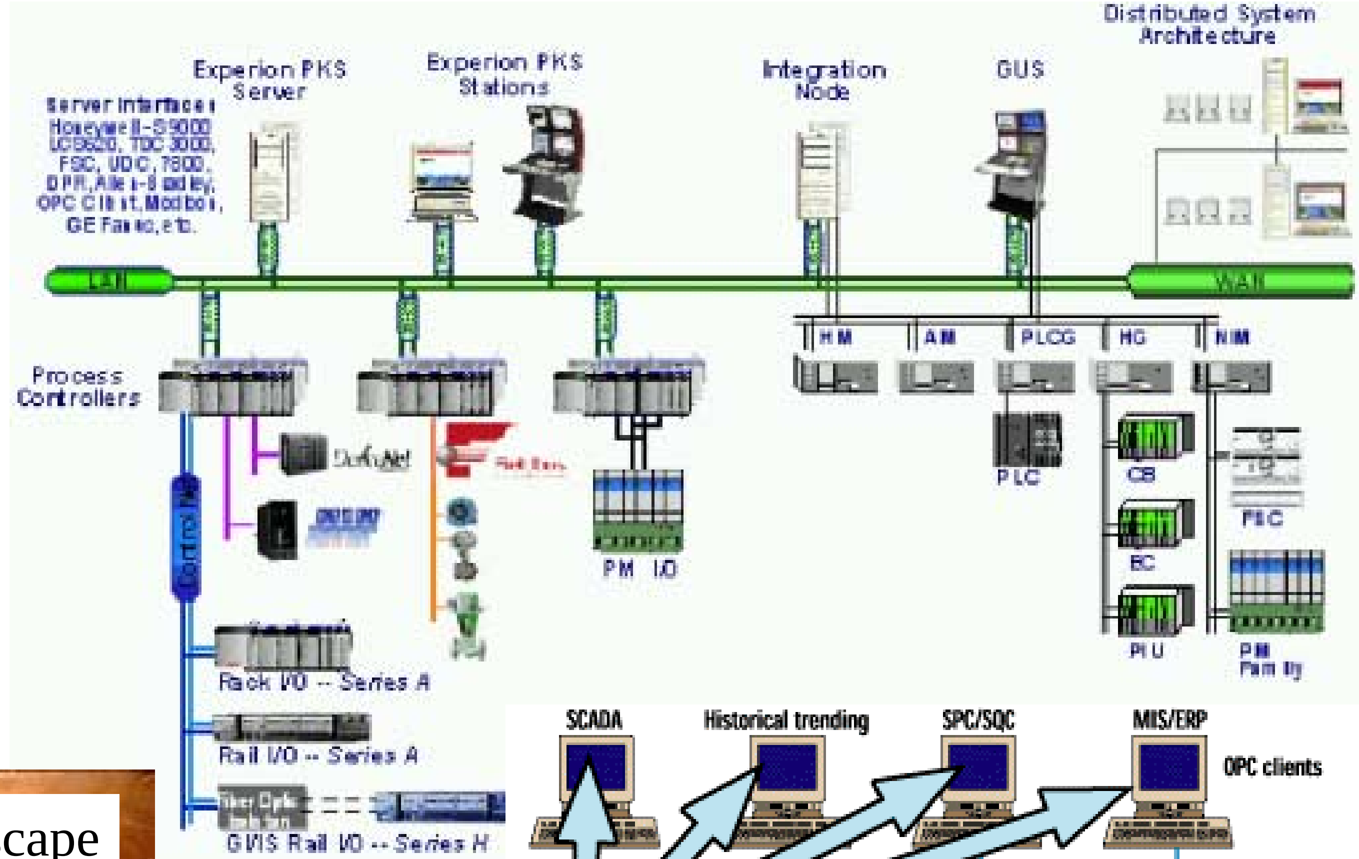
$$\delta r(t) = f_1 \Delta V_x(t) + f_2 \Delta V_y(t) + f_3 \Delta X(t) + f_4 \Delta Y(t)$$

1975 - Distributed Control System

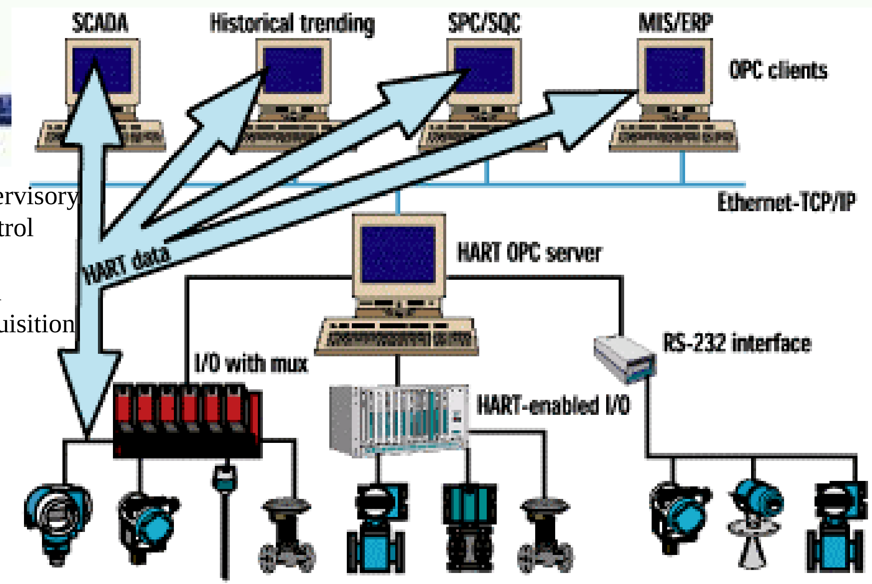
- 1963 - Direct digital control was introduced at a petrochemical plant. (Texaco)
- 1970 - PLC's were introduced on the market.
- 1975 - First DCS was introduced by Honeywell
- PID control, flexible software
- Networked control system, configuration tuning and access from one UI station
- Auto-tuning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

DCS example

Honeywell Experion PKS



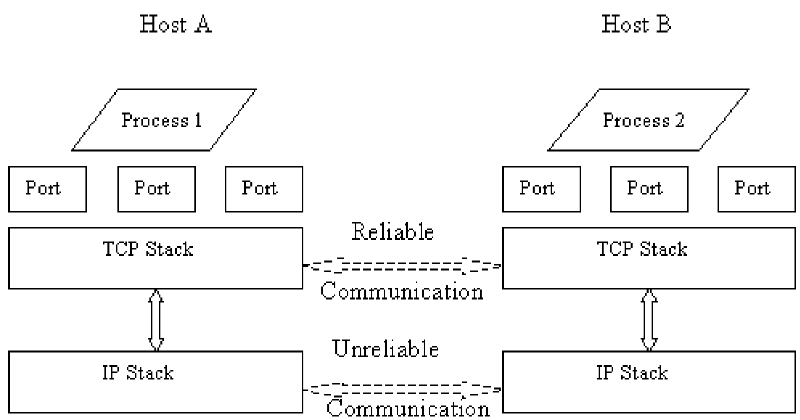
Supervisory
Control
And
Data
Acquisition

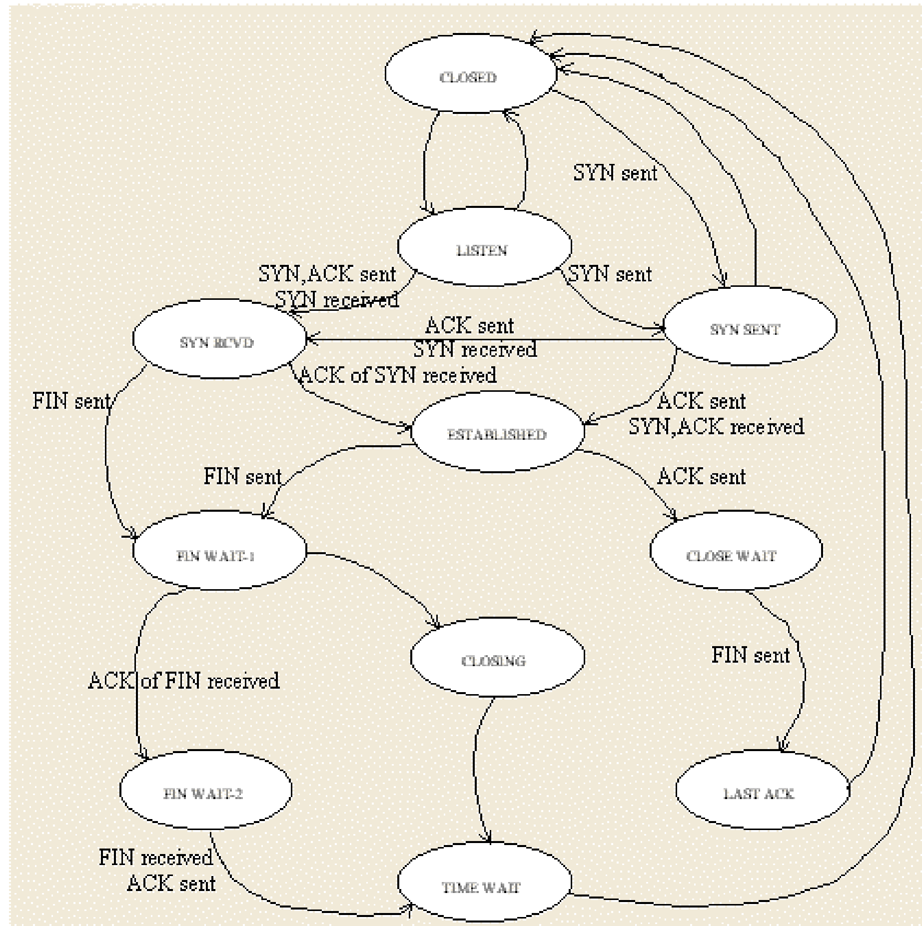


DCS - Rubs

- 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
- Autotuning technology
- Industrial digital control is becoming a commodity
- Facilitates deployment of supervisory control and monitoring

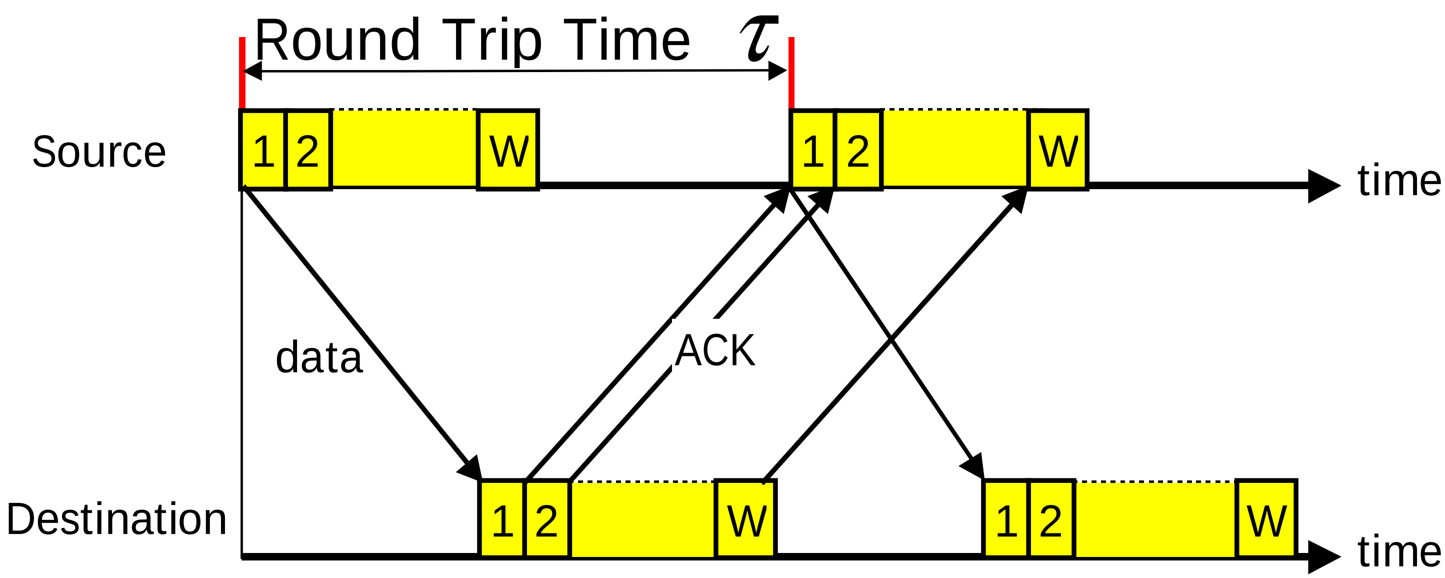
1974 - TCP/IP





- 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, 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

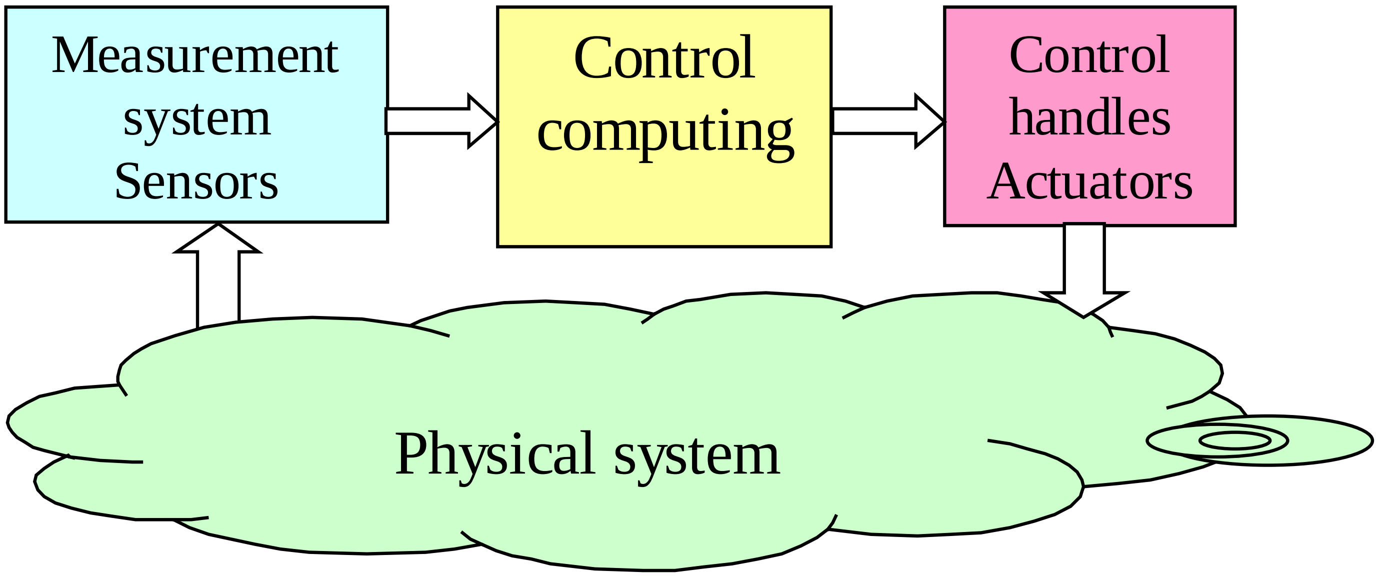
TCP flow control - Rubs

- 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.
- Most of analysis and systematic design activity in 4-5 last years and this is not over yet ...

Modern Control Engineering

- What BIG control application is coming next?
- Where and how control technology will be used?
- What do we need to know about controls to get by?

Modern Control Engineering

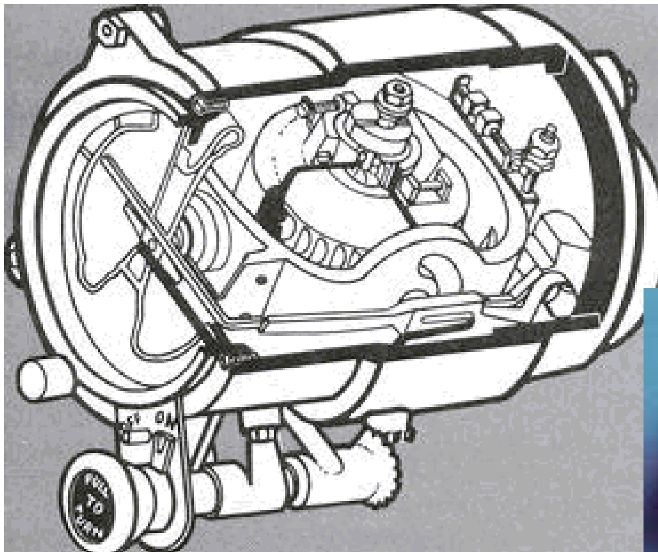


- This course is focused on **control computing** algorithms and their relationship with the overall system design.

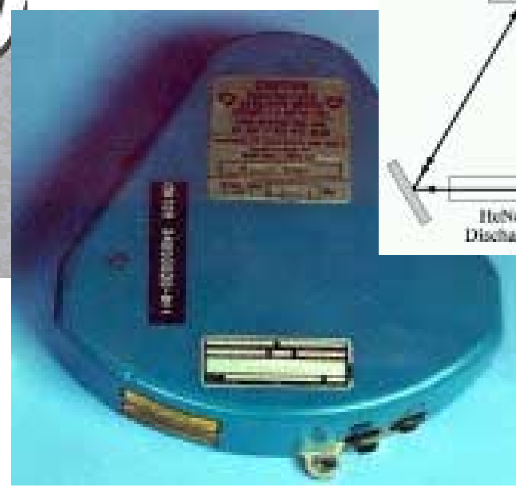
Modern control systems

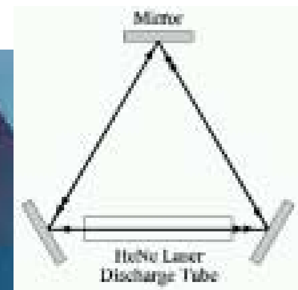
- Why this is relevant and important at present?
- Computing is becoming ubiquitous
- Sensors are becoming miniaturized, cheap, and pervasive. MEMS sensors
- Actuator technology developments include:
  - evolution of existing types
  - previously hidden in the system, not actively controlled
  - micro-actuators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

Measurement system evolution.
Navigation system example

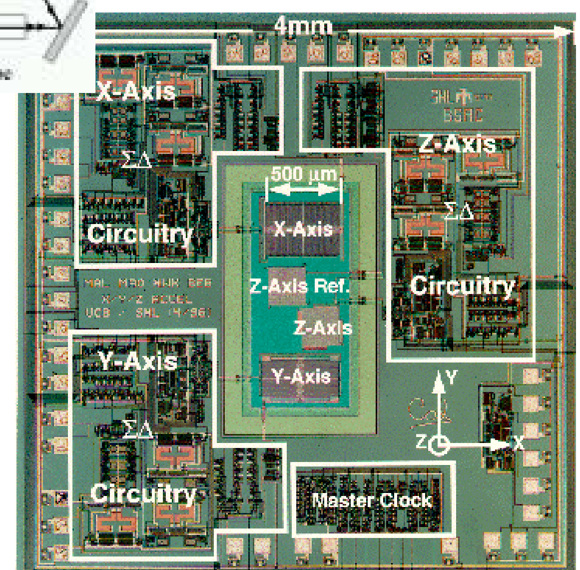


•Mechanical gyro by Sperry – for ships, aircraft. Honeywell acquired Sperry Aerospace in 1986 - avionics, space.





• Laser ring gyro, used in aerospace presently.

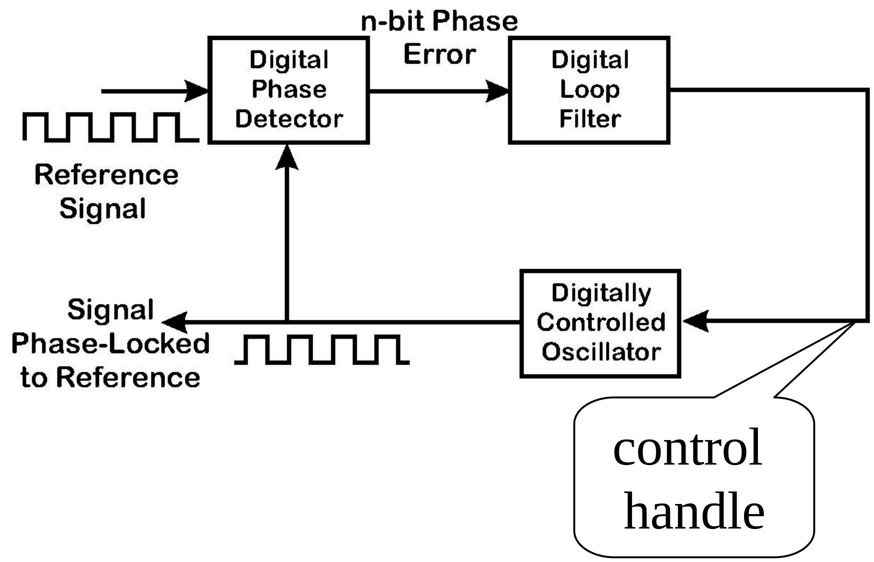


- MEMS gyro – good for any vehicle/mobile appliance.
  - (1") ^{3} integrated navigation unit

Actuator evolution

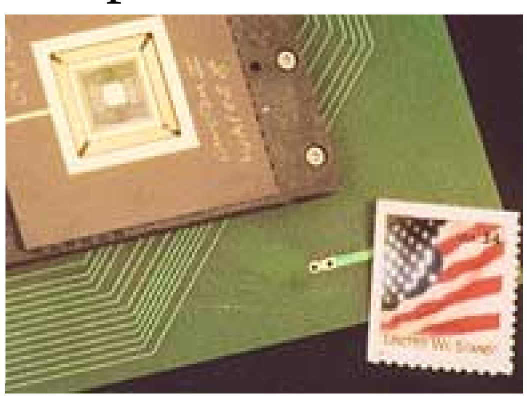
- Electromechanical actuators: car power everything

- Communication - digital PLL



- Adaptive optics, MEMS

μDM 140, 3.3 mm



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