EEE 481

Computer Controlled Systems

- Course outline

Wk 1: Introduction, Matlab and Simulink, PC104 platform, System simulation and Real-Time applications (Notes)
Wk 2: Computer Interfacing for Data Acquisition and Control, ADC-DAC, Signal conditioning, quantization (Notes)
Wk 3: Review of Z-transform and State Variables (Ch.2)
Wk 4: Z-transform and state variables, Linearization (Ch.2)
Wk 5: Sampling and Reconstruction, CT-DT conversions, Discretization (Ch.3, Notes)
Wk 6: Discretization, Open-loop DT systems (Ch.4, Notes)
Wk 7: Closed-Loop systems, Time/Frequency response characteristics (Notes, Ch. 5,6)
Wk 8-9: Feedback and Feedforward Control, Stability Analysis, Nyquist/Bode (Notes, Ch. 7)
Wk 10: PID controllers and tuning (Notes, Ch.8: Specs, PID)
Wk 11: PID tuning and Controller Discretization (Notes)
Wk 12: Feedforward Compensation (Notes)
Wk 13: State Estimation (Ch.9: Observers)
Wk 14: Model Identification (Notes, Ch. 10)
Wk 15: Sensors, Actuators (Notes)

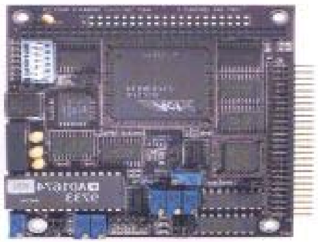
- (rev 9/2/15)

Introduction: The PC-104 Standard

- Low-power, general-purpose embedded applications
- Standard (small) size, stackable
  - Sound, PCMCIA, GPS, additional LAN, ADC-DAC,+…
- Advantech's PCM 3350
  - Stable geode processor (Pentium 300Mhz), on-chip PCI VGA, Intel82559 ER high performance Ethernet chip
  - 2 RS-232 serial ports
  - 128M RAM and FLASH memory (replacing the hard drive)

Introduction: The PC-104 Standard

- MATLAB compatibility: supported Ethernet chip for fast code download and testing.
  - Not crucial; one serial port can satisfy MATLAB’s requirement for a comm. link; but communication is very slow and the port is lost to the application.
  - check details in the web (advantech.com)
- Operating system: DOS or Windows (CE).
  - DOS suffices for downloading MATLAB’s real-time kernel and application program



Introduction: The PC-104 Standard

- Data acquisition and Control board: Diamond MM
  - Analog-to-Digital Conversion (ADC or A/D): 16 single ended or 8 differential analog inputs, 12-bit resolution, 2kHz software, 20kHz interrupt routine, 100kHz in DMA operation
  - Digital-to-Analog Conversion (DAC or D/A): 2 analog outputs, 12-bit resolution
  - 16 digital I/O lines (8 in, 8 out)
  - MATLAB compatibility: important to obtain quick results; but it offers only partial access to the board functions
  - web page: diamondsystems.com

Introduction to Computers

- Microprocessor, motherboard, memory
  - address, data, control buses
  - CPU: Arithmetic Logic Unit, Accumulator, Program Counter, Instruction Register, Condition Codes Register, Control Unit, Clock speed, MIPS, FLOPS
  - TPA (Transient Program Area): operating system, Commands, I/O, BIOS, Interrupt vector
  - XMS (Extended Memory System)

Introduction to Computers

- Memory characteristics (older data)

TYPE	AVG. CAPAC.	AVG. ACCESS	REL. COST
Cache	0.5M	2ns	10
Main	50M	20ns	1
Hard Disk	50G	10ms	10^{-2}
Floppy Disk	10M	500ms	10^{-3}
Magnetic Tape	5G	25s	10^{-3}
CDROM	600M	500ms	10^{-4}
DVDROM	8G	500ms	10^{-5}

Introduction to Computers

- I/O interfaces
  - isolated (IN-OUT instructions) and memory-mapped I/O
- Communication with external devices
  - polling: checking each device for service periodically (simple but inefficient)
  - interrupts: each device generates an interrupt that is serviced according to its priority level, in case of simultaneous arrivals

Introduction to Computers

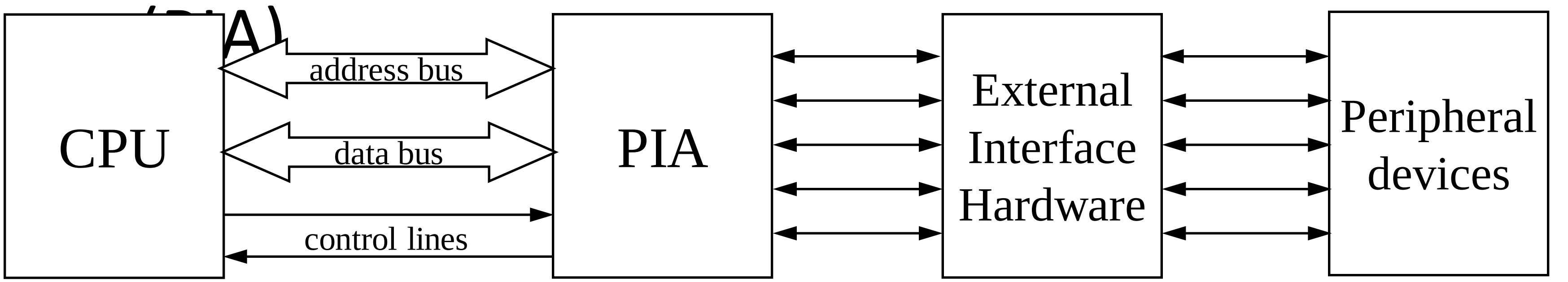
- Arithmetic Computations (7 x 6, 7/2)
  - Integer:
    - 0111 x 0110 = 01110+011100 = 101010
    - 0111 / 0010 = (011.1) = 011
    - Answer length increases by one bit in additions and one word in multiplications. Scaling and truncation is necessary for fixed word lengths
  - Floating point: (binary 5e3 format)
    - 0.11100e011 x 0.11000e011 = (0.01110+0.00111)e{011+011} = 0.10101e110
    - 0.111e011 / 0.100e010 = (1.11)e{011-010} = 0.111e010

Introduction to Computers

- Math coprocessors perform a large variety of arithmetic operations (+,-,x,/,sqrt,sin,log,…)
  - fast and high precision
  - hardware implementation of operations
  - computation uses algorithms and look-up tables
  - Newer CPUs have a built-in math coprocessor; nowadays, they are only absent in very-low-cost, or very-fast applications

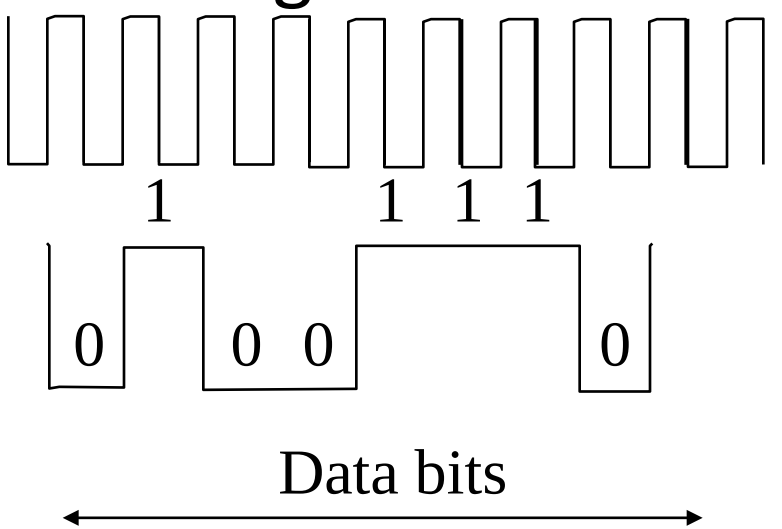
Introduction: Parallel Communication

- Timing circuits: counters and clocks
  - Real-time applications require independent clocks that are not affected by processor operations
- Parallel I/O port, parallel interface adapter (PIA)



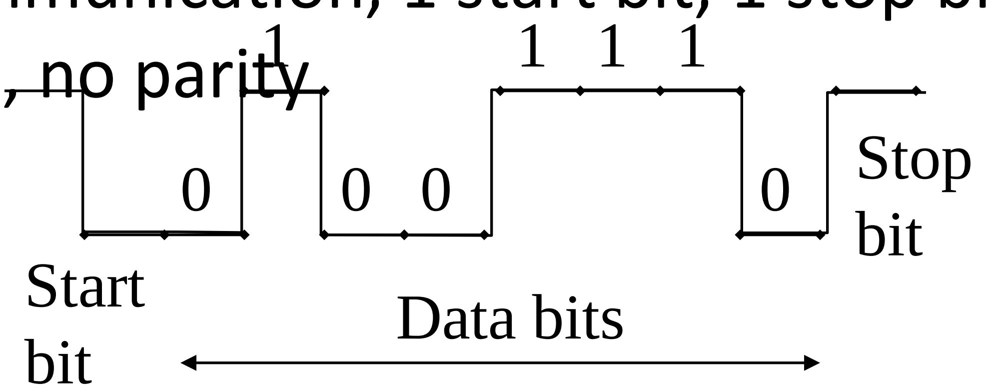
Introduction: Serial Communication

- Serial I/O port: transmission and reception one bit at a time
- Synchronous serial communication: separate clock signal



Introduction: Serial Communication

- Asynchronous serial communication
  - Start/stop/parity bits, baud rate (bits per sec.)
  - Universal Asynchronous Receiver Transmitter (UART)
  - Example of asynchronous serial communication, 1 start bit, 1 stop bit, 8 data bits, no parity



Introduction: RS-232

- Voltage level, DB-25, DB-9 connectors, ~20 kbaud (k-bits/sec), 50 ft. Physical-electrical-functional standards.
- As few as 3 pins used.
- Null modem or crossover cable: connection between computers instead of computer to device.

Introduction: Plug-in-slots

- Slots: electrical connections to CPU and other parts
  - Diskette drive, serial port, memory expansion, data acquisition and control, sound card.
  - Configuration: interrupt request level (IRQ), I/O port address, direct memory access (DMA) channels

Introduction: Bus

- Bus:
  - Industrial Standard Architecture (ISA), Extended ISA (EISA)
  - The “plug-and-play” concept
  - Peripheral Component Interconnect (PCI) bus:
    - PCI chip between slots and processor, uses registers to store configuration info
    - high throughput tasks
    - No need for jumpers or dip switches and no conflicts

Introduction: Bus

- Personal Computer Memory Card International Association (PCMCIA)
  - Memory and modems for portables.
  - More devices (Ethernet, SCSI interface, CD-burners, data acquisition, etc)
  - Fast access (but recent USB standard offers a convenient alternative)
- Small Computer System Interface (SCSI): high speed parallel interface bus (daisy chain)

Introduction: Computer Languages

- Machine-assembly
- BASIC (high-level, interpreter-based, low storage requirements)
- C (high level, transportable, efficient)
- MATLAB (and others; C-based-kernel, arrays, very-high-level math macros inv(A), A*B)
- Simulink: MATLAB GUI, system simulation, block diagram definitions

Introduction: Computer Languages

- MATLAB/SIMULINK: expansion via toolboxes (collection of functions written in MATLAB, (or C, Fortran, then converted to an executable .dll or .mex for older versions)
- Recent developments: ability to compile MATLAB code and create stand-alone executables
- xPC, xPC-target: real-time stand-alone applications from SIMULINK code

Introduction: Computer Languages

- xPC: Ability to perform rapid prototyping by constructing real-time code with very-high-level GUI.
  - Good for standard I/O interfacing
  - Easy-to-maintain code (SIMULINK)
  - More complicated applications may require the development of new interface drivers
  - More info: on-line or web help from mathworks

Introduction: MATLAB

- MATLAB: Initially, computations with arrays e.g., A*b, A\b, eig(A), svd(A). Then expanded to address all “signal and system” topics.
- Basic file structure:
  - m-files: scripts or functions, with high level interpreter commands
  - mat-files: data in binary format (see LOAD/SAVE)
  - .dll: executable code

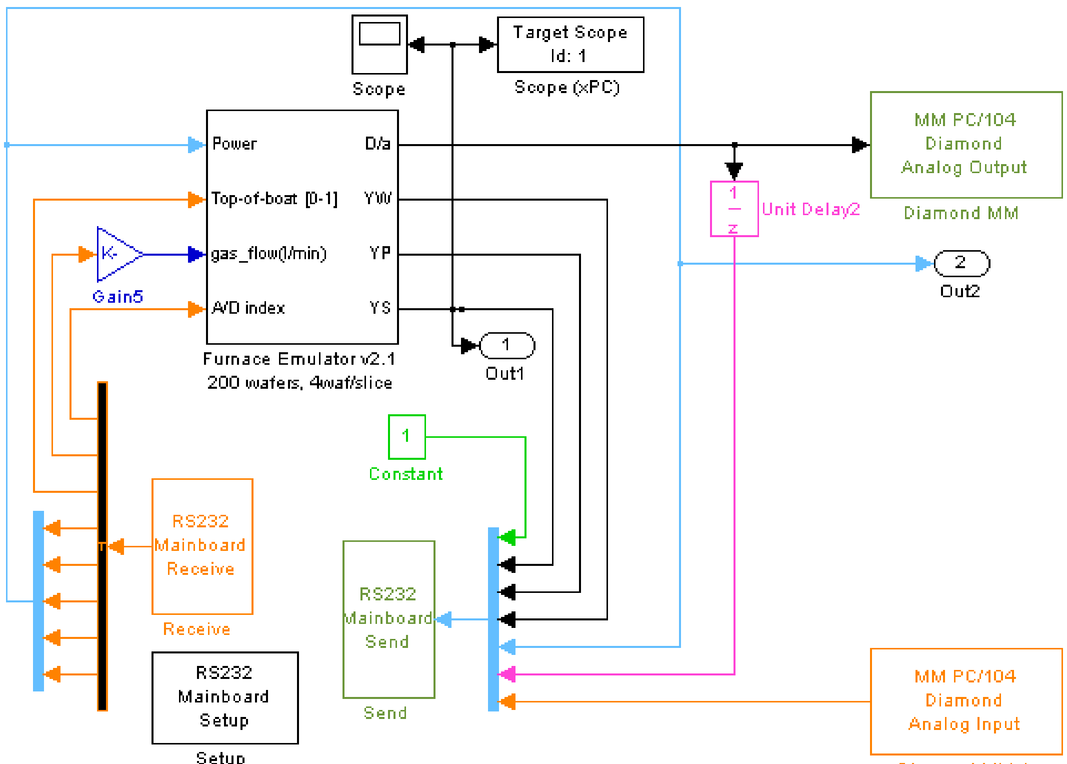
Introduction: MATLAB

- Other commands
  - “help:” the most important command…
  - Commands for systems, control, signal processing, image processing, neural networks, …
  - arranged in “toolboxes”, i.e. directories with m-files
    - tree structure is only important for indexing and help but not for operation
    - Matlab will only look in the defined “path” for functions and data. A useful trick is to copy a shortcut in each data directory having an empty option at “Start in”. Then, double click the shortcut to open a MATLAB session and include the current directory in the path.

Introduction: MATLAB

- SIMULINK: MATLAB GUI to define simulation systems in block-diagram form
  - mixed continuous and discrete time, but not as “easy” as it used to be…
  - .mdl files contain an ASCII description of the parameters of each block
  - s-functions: key building block of the simulator, relying on the concept of the state; fairly easy to create custom blocks but becomes complicated if real time executables are created

Introduction: MATLAB



A SIMULINK example with:

A main block (Furnace emulator),

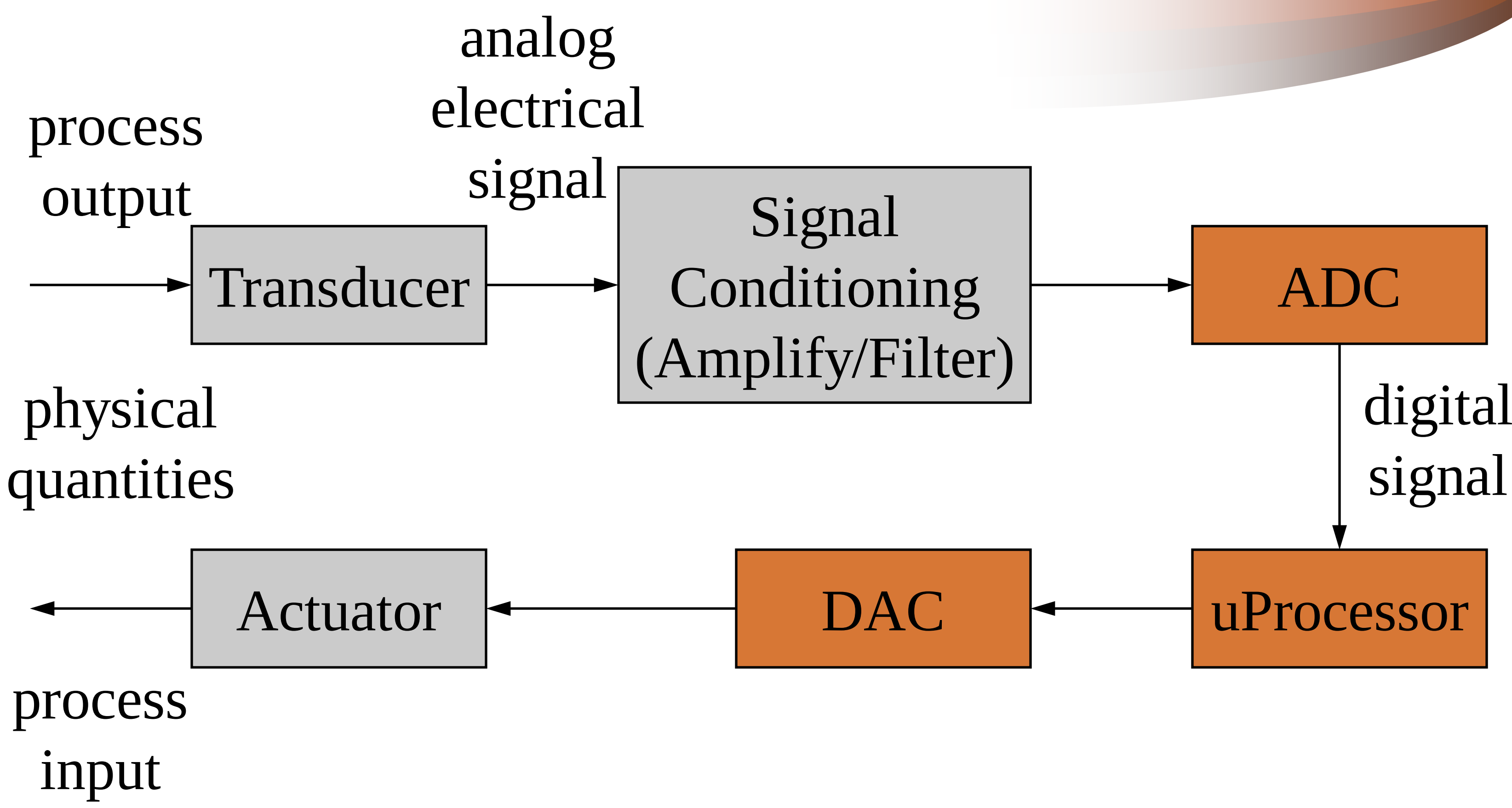
RS-232 I/O,

Analog I/O, and

Screen output

More details in Furnace Notes.doc

Typical Configuration of a data acquisition and control system



Computer Interfacing for Data Acquisition and Control

- Data acquisition: discretization in time and quantization in state-space
- Sampling theorem, Nyquist frequency.
  - No-aliasing condition: Tsample = 1/(2 fmax)
  - Practical selection: Tsample = 1/(20fmax)
  - Use of anti-aliasing filters (Review!)
- Quantization resolution = full scale/2^n

Digital Signals

- PLC (Programmable Logic Controllers): well suited for Boolean Algebra implementations
  - E.g., Alarm when
    - low level and high pressure
    - high level and high temperature
    - high level and low temperature and high pressure
  - Analog implementation of a two-level signal with hysteresis: op-amp with positive feedback

Digital Components

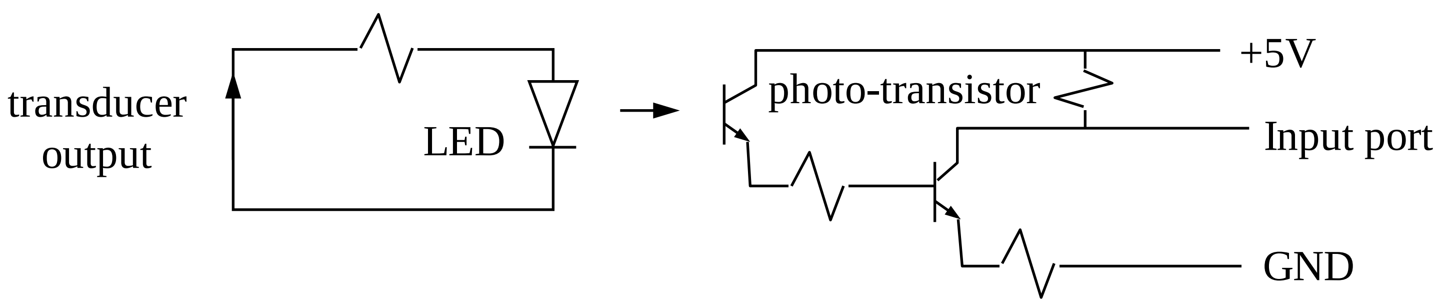
- TTL, CMOS
  - Digital logic circuits will not drive actuators directly
- Electromechanical or solid-state relays
  - Switch high currents and voltages
  - Considerations: wear, corrosion, arcing, robustness, speed, noise immunity
- Encoders, counters, latches, tri-state buffers

Analog Circuitry

- The 4-20mA standard: current signal information ranging between 4 and 20mA.
  - 4mA minimum to check integrity, 20mA maximum to indicate malfunctions
  - can drive various instrumentation devices with standardized input
  - many actuators follow the same standard and work with 4-20mA inputs
  - 3-15psi (20-100kPa) pneumatic loop standard

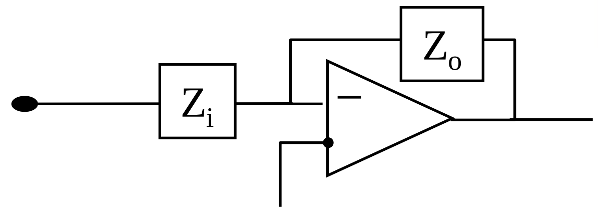
Analog Circuitry

- Signal buffering with op-amps
  - voltage following to minimize loading in the sensor and electrically isolate the sensor from the circuit
- Offset correction, filtering of unwanted frequencies (typically with low-pass filters)
- Isolation: opto-couplers, magnetic coupling



Analog Circuitry

- Op-amps:

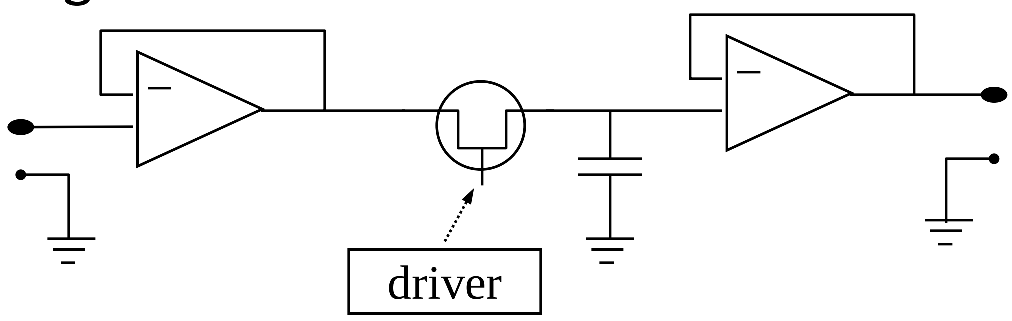


$$Vout = -\frac{Z_o}{Z_i} Vin$$

  - Active filters, low-pass, high pass, notch, etc.
  - Voltage followers (high input impedance, low output impedance)
  - Summation, difference, current-to-voltage conversion, voltage-to-current conversion
  - Nonlinear function inversion (when Zo = diode (exponential $j = e^{aV_o}$) => logarithmic amplifier

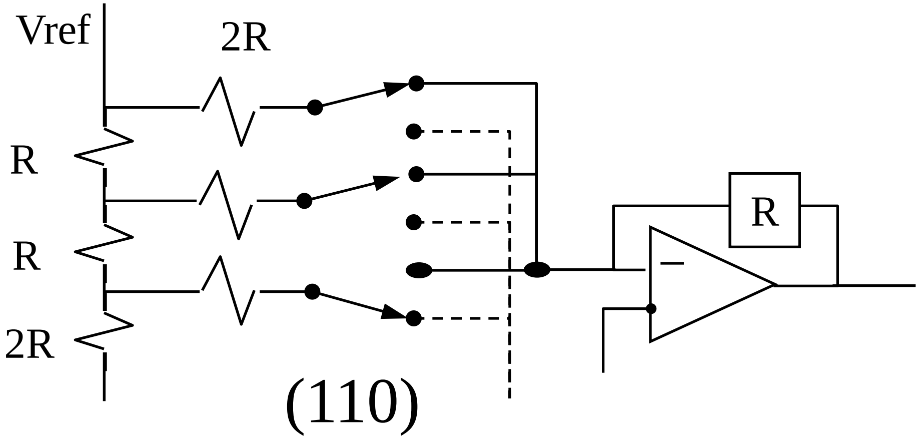
Analog Circuitry

- Analog Switches (JFET, MOSFET).
  - In Multiplexers and Sample-and-Hold circuits
  - S&H example:
    - computer controlled switch (digital out)
    - hi-quality capacitor maintains “constant” voltage during conversion time



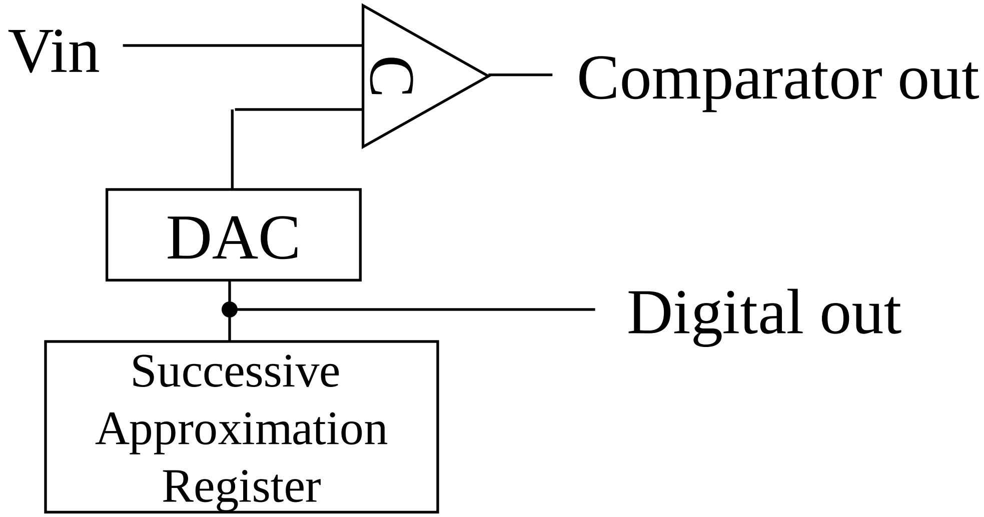
DAC-ADC

- DAC
  - “Binary ladder” networks (requires large resistances)
  - “R-2R ladder” network



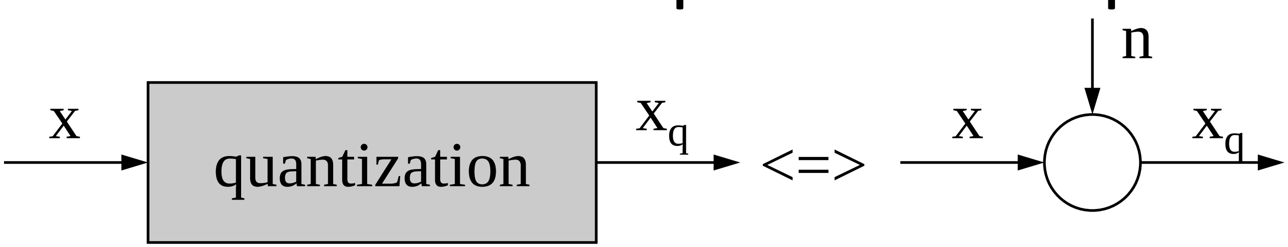
DAC-ADC

- ADC
  - Counter or ramp (slow, 2^n cycles)
  - Dual slope (noise averaging, slow)
  - Successive Approximation (fast, n cycles)



Quantization

- A special type of error: uncertainty reduction but with reduced accuracy
- 12-bit A/D, 0-5V =>$5/2^{12}$ =1.2mV resolution
- Model of the quantization process



n: random noise, uniform distribution $[-1/2^{n+1}, 1/2^{n+1}]$

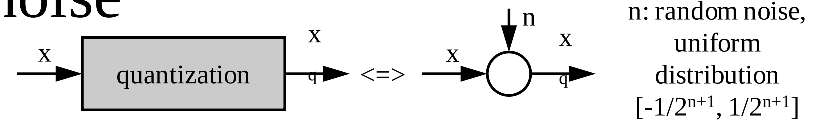
- Signal conditioning: Scaling to full range

Quantization

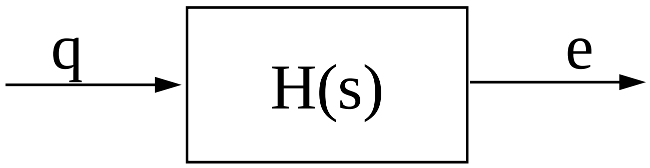
- Need for scaling:
  - Temperature range 0-2000^{o}C. Thermocouple output 0-30mV (assumed linear). 12bit A/D, 0-5V. Resolution: 1.2mV (from before) ~ (2000/30m)*1.2m = 80 ^{o}C => measurement = value +/- 40^{o}C!
  - Amplify TC measurement by 5/0.03 = 166.67. Resolution: (2000/5)*1.2m = 0.48 ^{o}C (reasonable)

Quantization II

- Quantization issues in Filtering and Control
  - Finite precision introduces errors in the computations as well as in the filter implementation.
  - Fixed-point arithmetic: bounded noise
  - 3 classes of errors:



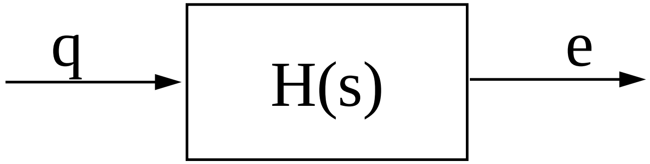
    - 1. A/D conversion: Type 1 errors due to signal quantization. Typical error is $^1/_2$ LSB
    - Multiplication: Type 2 errors due to signal quantization and truncation. Loss of several LSBs
    - Coefficients: Type 3 errors due to finite wordlength in filter implementation. Can cause filter instability. More important in FeedForward control.



Quantization II

- Type 1 and 2 quantization errors
  - Modeled as independent random noise with uniform distribution.
  - Error analysis: Compute the overall transfer function H(s) from the quantization error(s) “q” to the output of interest “e” and use an appropriate metric to quantify the effect of q on e
    1. Maximum error bound (very conservative)
    2. RMS error bound (usually conservative)
    3. Variance (good estimate, most appropriate for this case)

    Note: The conservatism of the estimate does not mean that the metric is not important, just that the analysis is not tight.



Quantization II

- Error bounds:

$$\text{Max.Amplitude}: \quad \| e \|_\infty \le \| H \|_{i\infty} \| q \|_\infty$$

$$where: \quad \| H \|_{i\infty} = \int | h(t) | \, dt, \quad h(t) = L^{-1}\{H(s)\}$$

(MATLAB: `sum(abs(impulse(H)))*DT`)

$$\text{RMS}: \quad \| e \|_{RMS} \le \| H \|_{i2} \| q \|_{RMS}$$

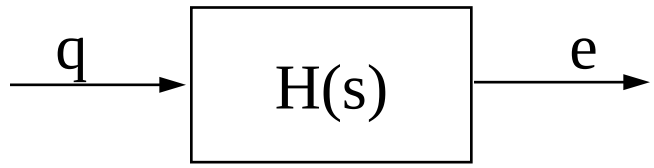
$$where: \quad \| H \|_{i2} = \max_w | H(jw) | \quad (for\ stable\ H)$$

(MATLAB: `norm(H,inf)`)

$$\text{Variance}: \quad \text{var}(e) \le \| H \|_2^2 \ \text{var}(q)$$

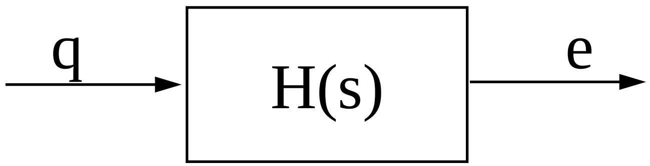
$$where: \quad \| H \|_2^2 = \frac{1}{2\pi} \int trace(H^*(jw) H(jw)) dw$$

(MATLAB: `norm(H,2)`)



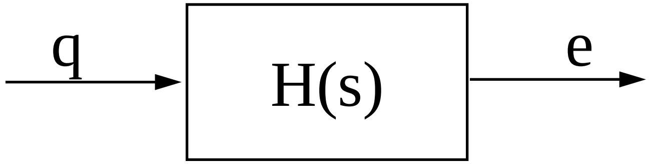
Quantization II

- Example:
  - Consider the plant P(s)=1/s, with the controller C(s)=(s+1)/s. Analyze the effect of a 10-bit input quantization on the output.
  - Discretization interval 0.01s, ZOH
  - $H = P/(1+PC) = s/(s^2+s+1)$
  - $Hd = 0.01(z-1)/(z^2-1.99z+0.9901)$
  - **CT:**`t=[0:.001:50]';h=impulse(H,t);plot(t,h);Hii=sum(abs(h))*.001`
  - Hii =1.306, Hi2 = norm(H,inf) = 1, H22 = norm(H,2) ^2 = 0.5
  - **DT:**`k=[0:10000]';h=impulse(Hd,k*.01);plot(k,h);Hii=sum(abs(h))`
  - Hii =1.3181, Hi2 = norm(H,inf) = 1.0044, H22 = norm(H,2) ^2 = 0.0051



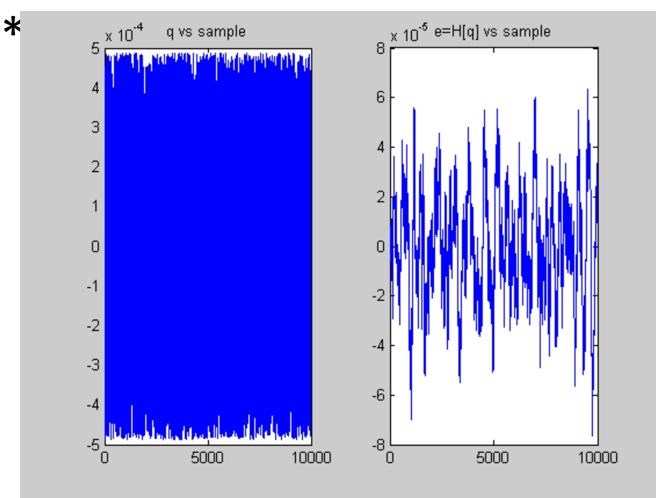
Quantization II

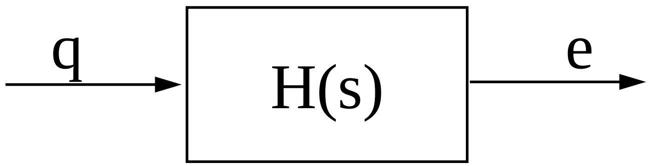
- Example (cont): Compute bound estimates
  - $q_{max}=1/2^{11}$, variance (uniform density) = $q_{max}^2/3$ = 7.947e-8, RMS ~ sqrt(var) = 2.819e-4
- max(|e|) < Hii q_{max} = 6.4359e-004
- RMS(e) < Hi2 RMS(q) = 2.8313e-004
- var(e)<H22 var(q) = 4.0337e-010
- The variance estimate appears to be much better than the RMS: sqrt{var} = 2.0084e-005 << 2.8313e-004



Quantization II

- Example (cont): Evaluate the estimates by simulation
- qm=1/2^11 ;q=(rand(10000,1)-0.5)*2*qm;k=[0:10000-1]';subplot(121),plot(k,q), title('q vs sample')
- Hd=fbk(c2d(P,.01),c2d(C,.01)),e=lsim(Hd,q);subplot(122),plot(k,e),title('e=H[q] vs sample')
- [max(abs(e)),sum(abs(h))*max(abs(q))] = 6.2659e-005 6.4352e-004
- [rms(e),norm(H,inf)*rms(q)] = 1.9416e-005 2.7953e-004
- [var(e),norm(H,2)^2* … 2e-010





Quantization II

- **Comments:**
- The max abs estimate is conservative by an order of magnitude.
- The var estimate is much better than the RMS.
- However, from the theory we know that the RMS bound is tight. The apparent discrepancy is due to the fact that var is defined for stochastic signals and RMS^2 is just its estimate from one realization. The variance estimate is good for stochastic inputs only and it is not an upper bound for deterministic signals as the next computation shows:
  - z=sin(.01*k); y=lsim(H,z);
  - [rms(y),norm(H,inf)*rms(z)]=7.0490e-001 7.1171e-001
  - [var(y),norm(H,2)^2*var(z)]=4.9686e-001 2.5490e-003
  - Notice that norm(H,2)^2*var(z) is NOT a bound on var(y) any more!
  - But the bound norm(H,inf) *rms(z) on rms(y) is now tight.

Quantization II

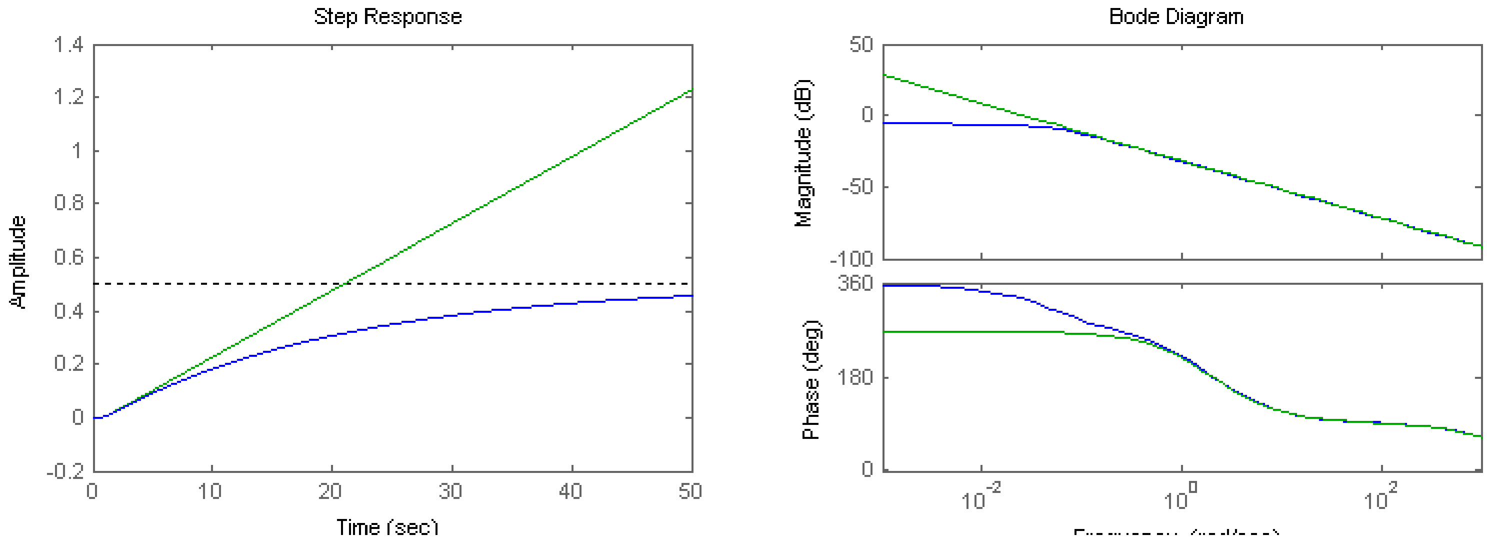
- Quantization issues in Filtering and Control
  - Due to the sensitivity of roots of polynomials to perturbations, the quantization of the filter coefficients can result in a different, possibly unstable filter
  - Different filter realizations can be more or less susceptible to quantization problems (parallel or cascades of 1st or 2nd order are preferred over direct forms)
  - Problems become more pronounced as the sampling rate increases (the discrete poles accumulate around 1 and there is loss of resolution)

Quantization II

- Example
  - Start with the heated-water-tube transfer function
  - P=tf([-.5 1],[.5 1])*tf(1,[40 2])
  - Discretize: PD=c2d(P,.001)
  - Enter the same transfer function with 4 significant digits: PD2=tf([-2.495e-5 2.5e-5],[1 -1.998 .998])
  - The first is stable with poles 9.9995e-00, 9.9800e-001
  - The second is unstable with poles 1.0000e+000, 9.9800e-001

Quantization II

– The difference is apparent in terms of step and frequency response



Quantization II

– Repeat for sampling time 0.1:

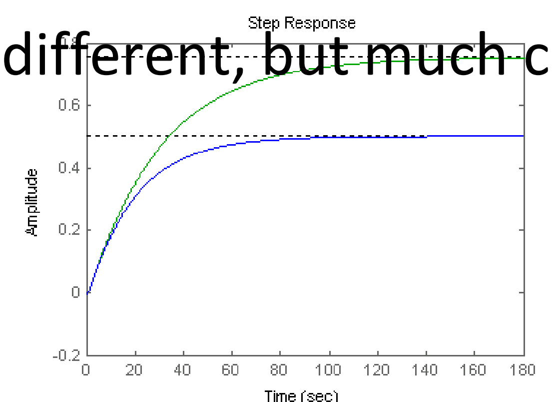
– Discretize: PD=c2d(P,.1)

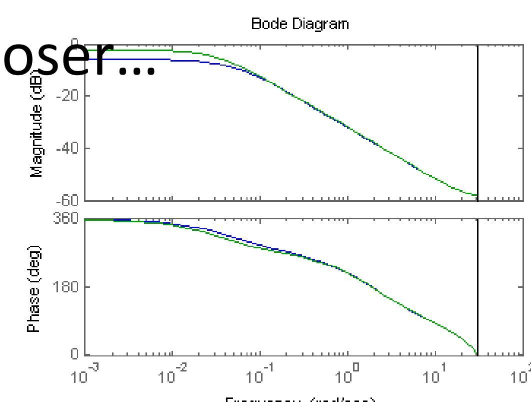
– Enter the same transfer function with 4 significant digits:
PD2=tf([-.002026 .002478],[1 -1.814 .8146],.1)

– The first is stable with poles 9.9501e-001 8.1873e-001

– The second is stable with poles 9.9672e-001 8.1728e-001

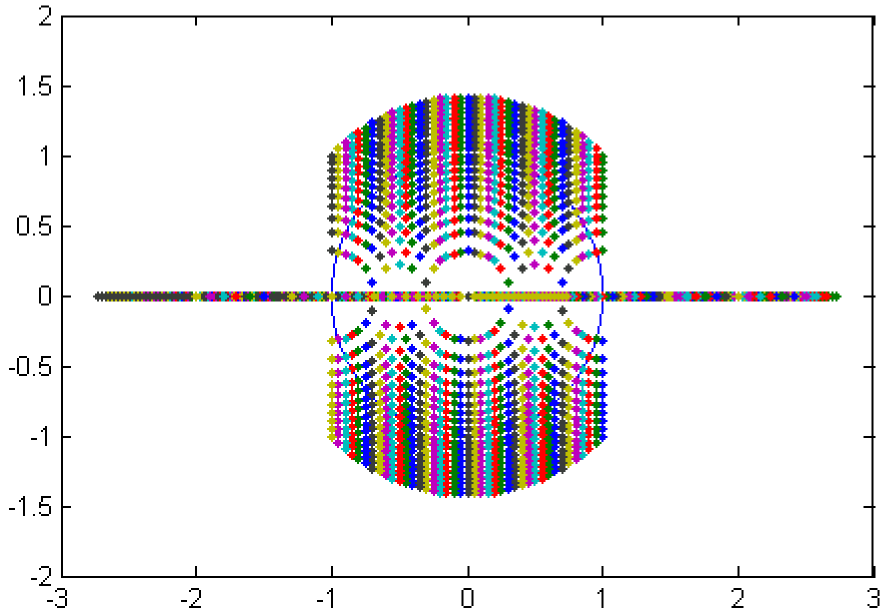
– Still different, but much closer…

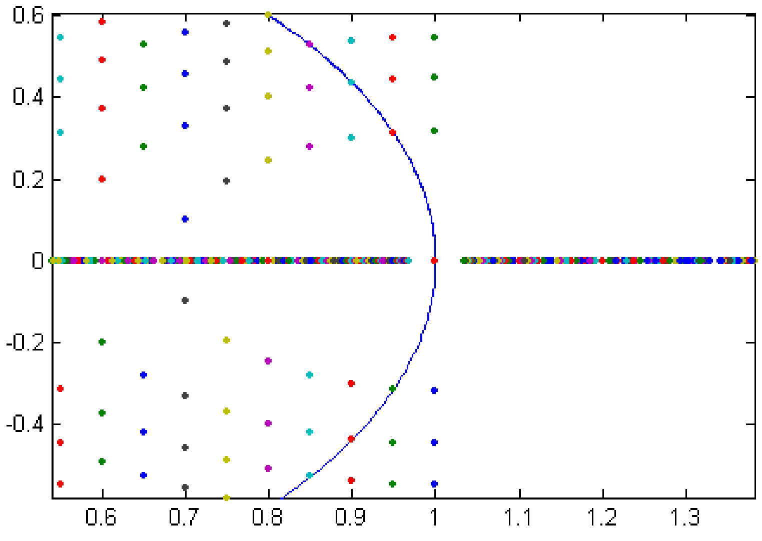




Quantization II

- Some insight
  - roots of 2nd order polynomial whose coefficients, are quantized to 0.1





Cables

- Flat cables: 1-10V, 100mA
- Twisted pair, shielded or unshielded
- Coaxial (less interference but not too popular)
- Digital connections, cheaper for low data rates
- Buffering (amplifying) and latching, for signals on a bus

Data acquisition and control with standard add-on cards

- Multifunctional cards: A/D, D/A, digital I/O, counter/timer operations
  - 4-16 multiplexed A/D, 1-2 D/A, (max rate quoted for all channels combined)
  - programming commands (in C or high-level)
- Industrial signal conditioners
  - thermocouple linearization and cold junction compensation, filtering and amplification, strain gauge linearization, etc.

Data acquisition and control with standard add-on cards

- Signal Conditioning Extensions for Instrumentation (SCXI): high performance system for use with PCI
- Remote I/O modules. Standard RS-232, RS-485 interfaces for 15-bit measurement resolution
- IEEE-488 GPIB (general purpose interface bus)
  - rigidly defined, 1Mbyte/s transfer rates, multiple (15) devices to a single network

Data acquisition and control with standard add-on cards

- IEEE-488 GPIB hardware specs
  - total cable length 20m, individual device cable 2m
  - 24 lines in the cable, clearly defined; 8 data, 8 handshaking, 8 grounding and shielding
  - star, daisy chain, mixed networks
- GPIB devices
  - Talkers, listeners, controllers; interconnected via back plane.

Data acquisition and control with standard add-on cards

- Backplane Bus
  - Board on which connectors are mounted; provides data, address, control signals
- STE Bus
  - 8 bit, 20 address lines (1MB memory), 4kB addressable I/O
  - Compact cards, robust two part connector, shock and vibration resistant
  - IEEE-1000 standard

Data acquisition and control with standard add-on cards

- VME Bus
  - Motorola design for the 32 bit 68000-based system.
  - 24MHz data transfer rate
  - 32 bit address bus
- VXI Bus (VME extension for instrumentation)
  - Improvement over GPIB in communication speed, synchronization and triggering
  - Various possible system configurations including GPIB

Microcontrollers

- Microprocessors with analog and binary I/O, timers, counters, to perform real-time control functions (8, 16, 32 bit)
  - Characteristics: 4kB ROM, 128B RAM, single byte instructions, built-in counters, timers, I/O ports
  - Intel 8051, 8096, Motorola MCH68HC11, etc.
  - DSP (Digital Signal Processors): special architecture for high speed numerical tasks. Separate data bus from instruction bus.

Microcontrollers

- The Arduino family
  - Inexpensive evaluation boards (low-medium capabilities)
  - Available drivers making their programming easy (albeit with some restrictions)
  - Large development forums (software and 3rd party hardware support)

Distributed Digital Control Systems

- Increased complexity is less of an issue
- Additional functions over older analog systems (redundancy, failure detection, communication, data storage, adaptation/scheduling)
- Overall more reliable, less susceptible to computational noise, controllers are not degrading with time
- Low cost

Distributed Digital Control Systems

- Process control applications
  - Plant automation
  - Programmable logic controllers (PLC, sequencing jobs)
  - Regulatory process control: single loop PID or Distributed Control System (DCS) for large-scale applications
  - Batch processes: repetitive nature; "run-to-run" optimization schemes
  - Advanced applications (identification and control)

Distributed Digital Control Systems

- Computer networks, different topologies
  - For control over networks, the issues of reliability, and deterministic message transmission must be addressed
  - Network communications: common modular set of rules for generating and interpreting messages
  - Open System Interconnection (OSI): 7-layer architecture; Physical, Data link, Network, Transport, Session, Presentation, Application

Distributed Digital Control Systems

- OSI components
  - Repeater, at the physical layer
  - Bridge, at data link layer
  - Router, at network layer
  - Gateway, at higher levels
- Communication protocols define connectors, cables, signals, data formats, error checking, algorithms for network interfaces and nodes

Distributed Digital Control Systems

- Communication protocols
  - Simple: polling and interrupt driven
  - Token ring and Token Bus
  - Carrier sense multiple access with collision detection (CSMA/CD)
    - IEEE 802.3. Check for network activity. If idle, a node may transmit, then the network becomes busy. In case of collision, transmission is aborted and a random wait time is introduced.

Distributed Digital Control Systems

- CSMA/CD
  - Simple algorithm, non-deterministic, priorities not supported, collisions a problem at high network loads, analog technology for collision detection
  - Ethernet is an implementation of CSMA/CD network. 10Mb/s, coaxial cable or twisted pair. E.g., National Semiconductor 3-chip implementation: Network interface controller (protocol, information movement), Serial network interface (clock), Coaxial transceiver interface (coaxial versions)
- Token ring and Token Bus

Distributed Digital Control Systems

- Several DCS platforms from major manufacturers
  - Honeywell, Foxboro, Fisher and Porter, Westinghouse, EMC control, Reliance Electric, Beckman Instruments
- Recently, PC or workstation based systems, supervising local embedded controller boards

Examples of Computer Control

- Industrial processes versus laboratory experiments
- Several aspects:
  - Process description and modeling
  - Sensors and actuators
  - Controller design (algorithm and structure)
  - Discretization and implementation
  - Auxiliary functionality

Examples of Computer Control

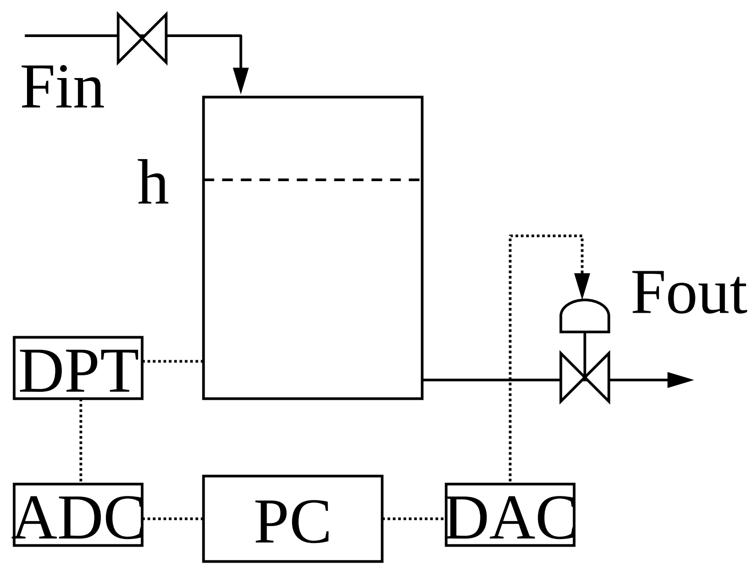
- Liquid level system
  - Tank - valve - pump in different configurations
  - Differential pressure transducer (translating to level). Other options: floaters, resistivity measurements.
  - Valve as a final control element (with or without a pump). Electric valve, pneumatic valve (common), electric actuation via I/P current-to-pressure converter

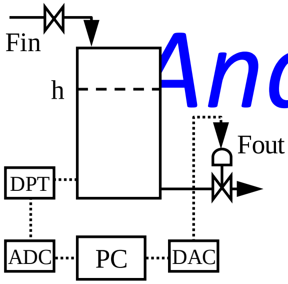
Analysis of the Liquid Level Control Experiment

- One example: control the level by manipulating the inlet stream or the outlet.
  - Fin, Fout: flowrates in and out. h: level
  - Bernoulli:

$$P + \frac{1}{2}\rho v^2 + \rho g h = const.$$

  - P: pressure, r: density,
  - g: grav. accel., v: velocity





Analysis of the Liquid Level Control Experiment

$$A_i \dot{h}_i = F_{in} - F_{out}$$ – inlet conditions

$$A_i v_i = A_o v_o$$ – incompressible flow

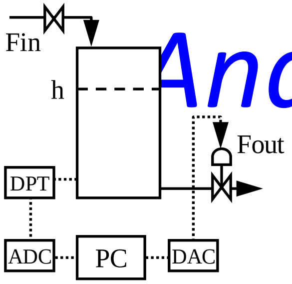
$$P_i + \tfrac{1}{2}\rho v_i^{\,2} + \rho g h_i = P_o + \tfrac{1}{2}\rho v_o^{\,2} + \rho g h_o$$ – Bernoulli

$$P_i = P_o,\ h_o = 0,\ A_i >> A_o \Rightarrow v_i << v_o \Rightarrow 2gh_i \cong v_o^{\,2}$$

$$\Rightarrow A_i \dot{h}_i = F_{in} - A_o v_o = F_{in} - A_o\sqrt{2gh_i}$$ – simplify

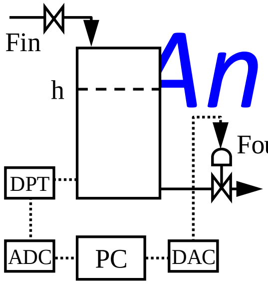
$$\Rightarrow \dot{h}_i = \frac{F_{in}}{A_i} - \frac{A_o}{A_i}\sqrt{2gh_i}$$

- A = cross section area, inlet-outlet
- “Ideal” flow



Analysis of the Liquid Level Control Experiment

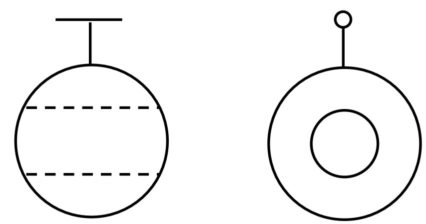
- ODE for h, nonlinear: slower than linear response for large levels h; faster for small h.
  - Tank drains in finite time
  - Addition of a pump: reduced sensitivity of outflow to liquid level in the tank
- Next, the manipulated variable: We open or close the valve, i.e., we effectively modify the outlet cross section area.



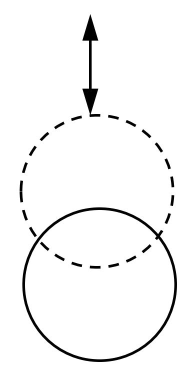
Analysis of the Liquid Level Control Experiment

- Valves
  - Many types with different characteristics (pressure drop, open/close speed, size, linearity, sealing).
  - Ball (common, e.g., manual/auto sprinkler valves at the store)

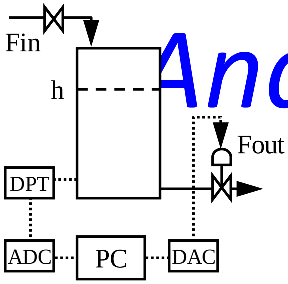
Ball, side and front view
(spherical housing not shown)



  - Gate (sliding in and out to restrict flow)
    - easier to compute cross section area

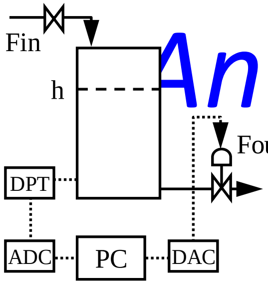


Disc-shaped Gate, front view



Analysis of the Liquid Level Control Experiment

- Let us select a gate valve with a motorized screw as an opening/closing mechanism.
- We manipulate the current to the motor or, in a high friction simplification, the motor speed.
  - Suppose that at max speed, it takes 2 sec from full-open to full-close
- Other options: Manipulate the set-point of a valve controller, for a %-open value; pneumatic valves with a I/P converter.

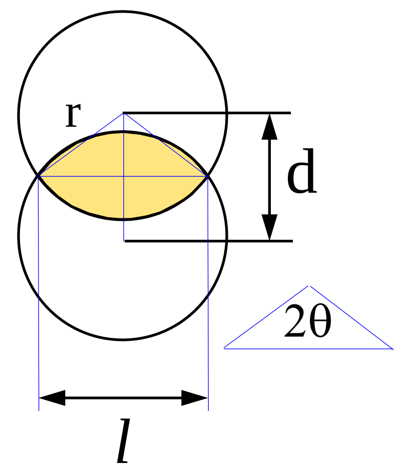


Analysis of the Liquid Level Control Experiment

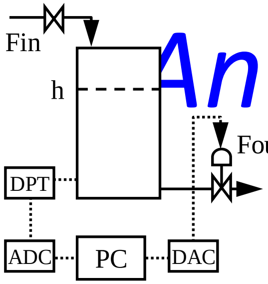
- Compute cross section area as a function of %-open (distance between gate center and pipe center)
  - shaded area = 2x[sector - triangle area]
  - $\theta = \cos^{-1}\left(d/2r\right), \; SECTOR.AREA = r^2 \cos^{-1}\left(d/2r\right)$

    $TRIANGLE.AREA = ld/4, \; l = \sqrt{4r^2 - d^2}$

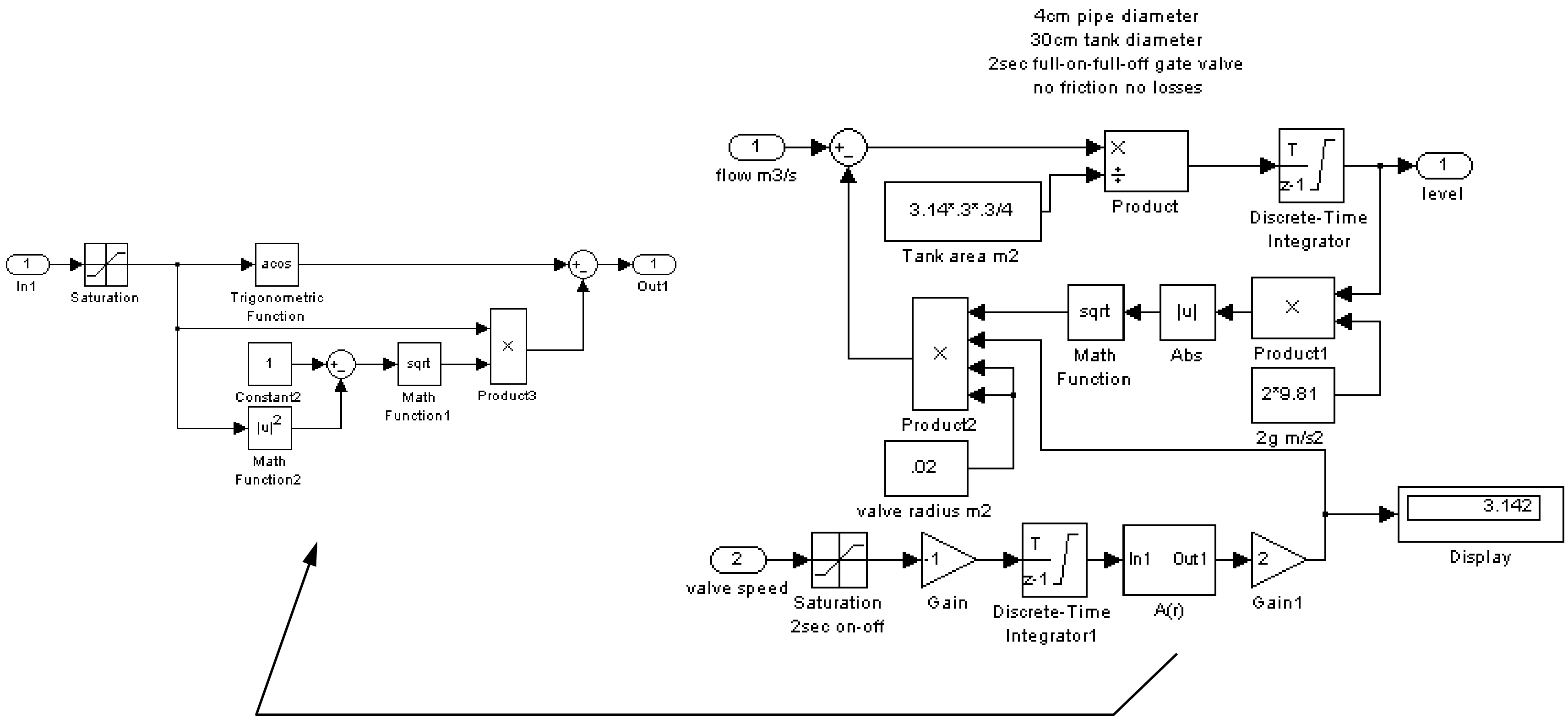
    $\Rightarrow \cdots \Rightarrow A_o = 2r^2\left[\cos^{-1}(D) - D\sqrt{1-D^2}\right], \; D = d/2r$
  - Relation to control input: $\dot{d} = u$

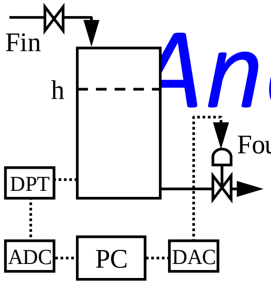


Analysis of the Liquid Level Control Experiment



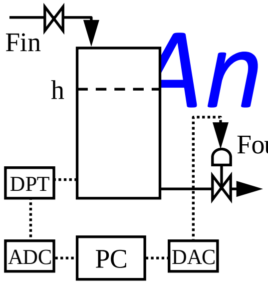
- Simulink Implementation





Analysis of the Liquid Level Control Experiment

- Simulink Implementation
  - Test the analytical no-inlet discharge time. $\dot{h} = \alpha\sqrt{h}$
  - Test analytical steady-state results for Fin constant.
  - Discretization: Estimate natural time constant and controlled (closed loop) time constant; sample an order of magnitude faster; check responses visually.
  - Use saturation nonlinear blocks to observe physical limitations

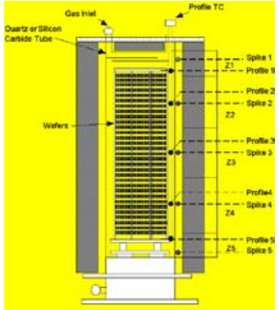


Analysis of the Liquid Level Control Experiment

- Simulink Implementation
  - Linearization (for analysis and controller design)
    - Derive variations around a steady state, analytically or using linmod (self study)
    - Parameters: 4cm pipe diam., 30cm tank diam.
    - Linearization equations (at a nominal steady state where h,D=const., D~0.5, δu = normalized in 0-1)

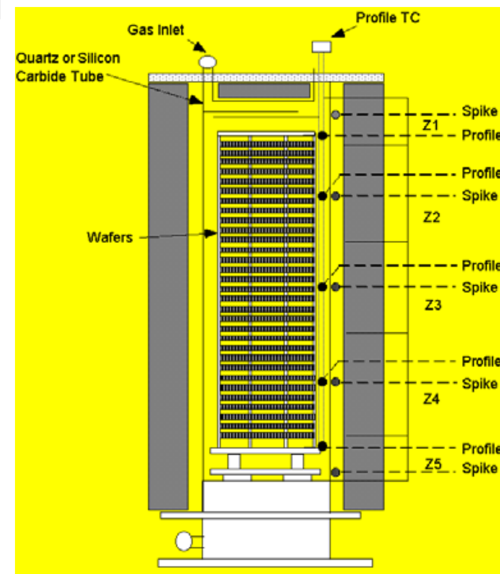
$$\delta \dot{h}_i = -\left.\frac{A_o(D)g}{A_i\sqrt{2gh_i}}\right|_{nom.ss} \delta h_i - \left.\frac{\sqrt{2gh_i}}{A_i}\right|_{nom.ss} \left.\frac{\partial A_o(D)}{\partial D}\right|_{nom.ss} \delta D$$

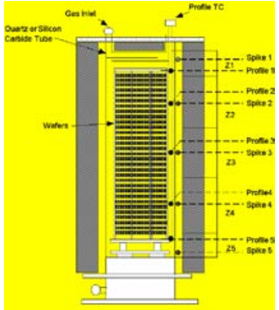
$$\delta \dot{D} = \delta u$$



Diffusion Furnace Temperature Control

- Multivariable system, approximating distributed sensing and actuation
  - Measure temperatures at different points inside the tube (profile) and outside of the tube, near the heating element (spike)
  - Apply heating power through SCR actuating modules roughly in the same zones
  - Accuracy is essential





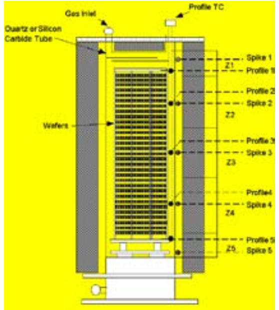
Diffusion Furnace Temperature Control

- Modeling:
  - Basic heat balance equation

$$mc_p\dot{T} = H_{in} - H_{out}$$

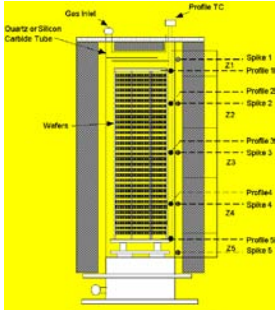
$$= q - hA(T - T_{ambient}) - \sigma FA(T^4 - T_{amb}^4)$$

    - m = mass, c_p = specific heat, T = absolute Temperature, h = heat transfer coefficient (convection), A = surface area, σ = Boltzmann constant (radiation), F = view factor, q = externally supplied heat
  - Apply to differential volumes and obtain a PDE model
    (details in EEE480 model notes and EEE482 Furnace notes)



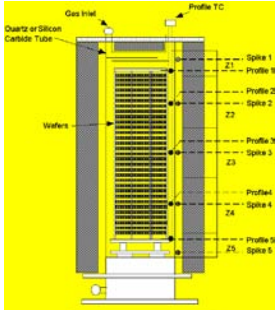
Diffusion Furnace Temperature Control

- Sensors: Thermocouples for high temperatures (some operations above 1000deg.C). Pyrometry is another option for single wafer reactors.
  – Issues: Cold-junction compensation, amplification, and table look-up linearization. RF interference may appear from SCR application of electrical power
- Actuators: SCR modules
  – Issues: resolution - switching transient trade-off



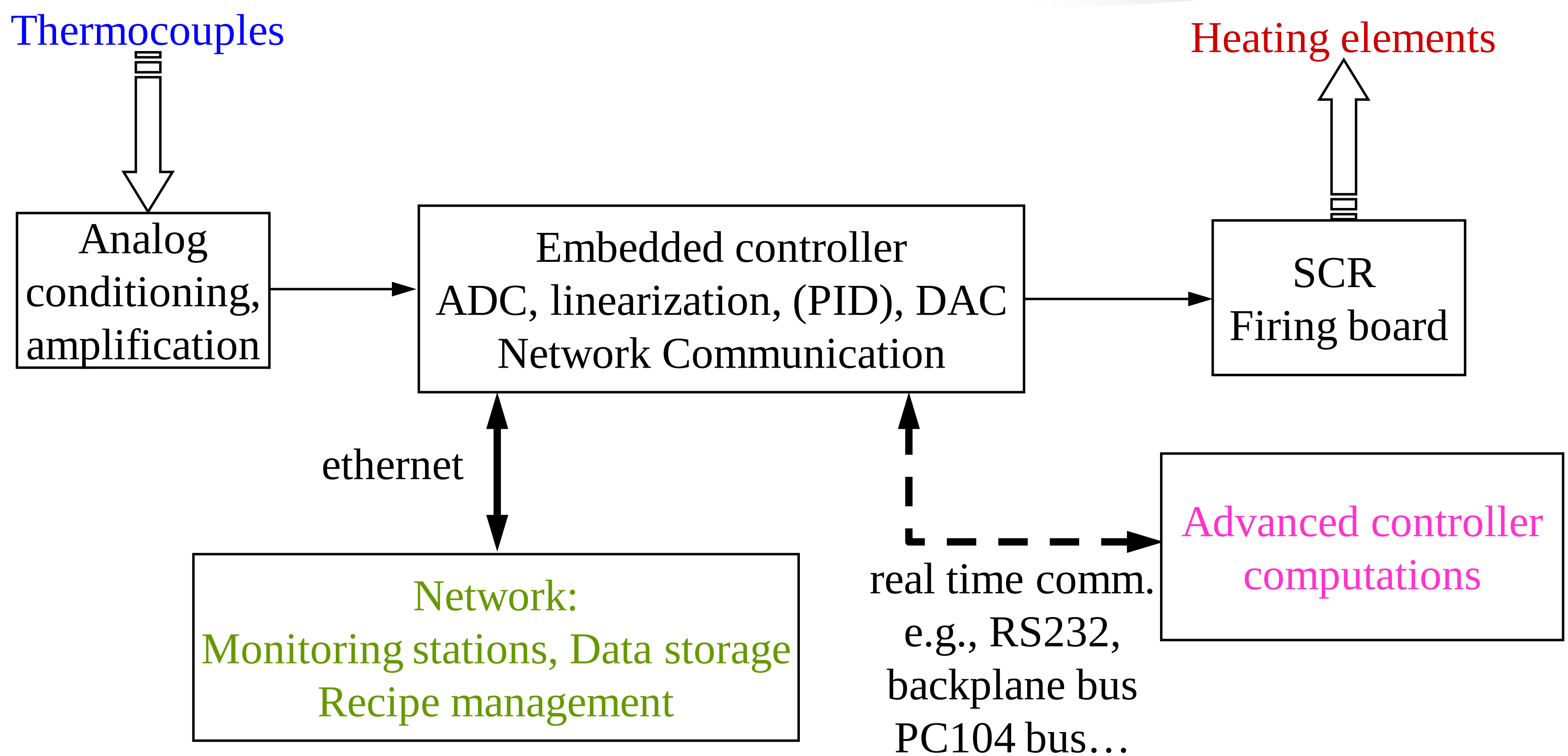
Diffusion Furnace Temperature Control

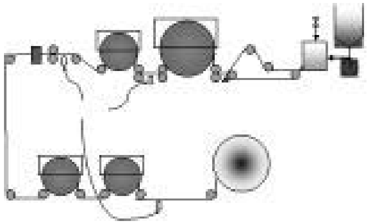
- Need for elaborate and precise controllers
  - Newer furnaces have more (5) heating zones for more resolution and improved uniformity (temperature coupling is higher than in the older 3-zone furnaces)
  - Due to radiation nonlinearity, different controllers may be necessary to cover a big temperature range
  - Nonlinearity and coupling are more pronounced in single-wafer rapid thermal processors (RTP), using arrays of heating lamps



Diffusion Furnace Temperature Control

- Controller communications





Control of Paper Machines

- Process description

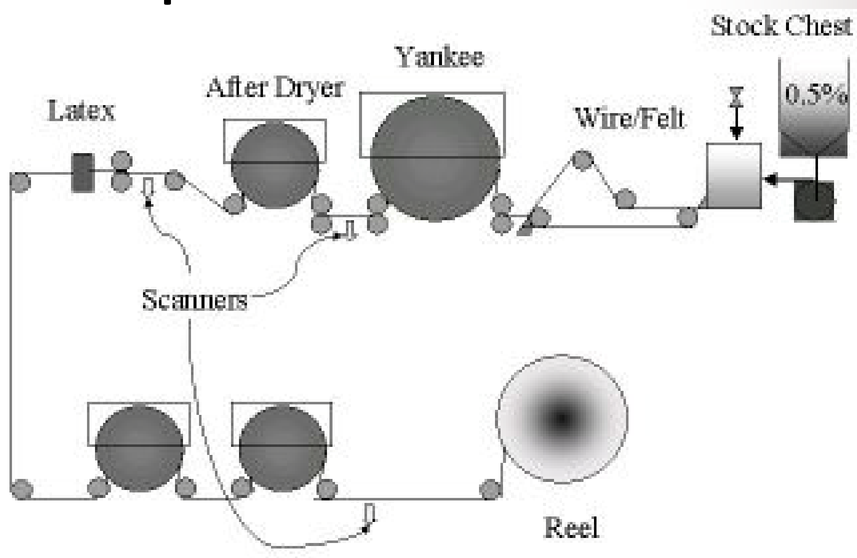
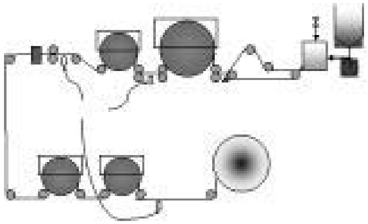


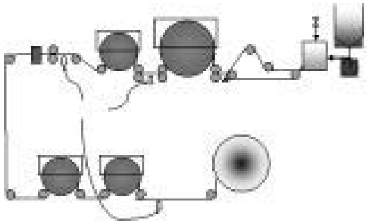
Figure 1. Paper Machine Schematic

- K. Tsakalis, S. Dash, A. Green, and W. MacArthur, "Loop-Shaping Controller Design From Input–Output Data: Application to a Paper Machine Simulator," IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 10, NO. 1, 127-136, JANUARY 2002



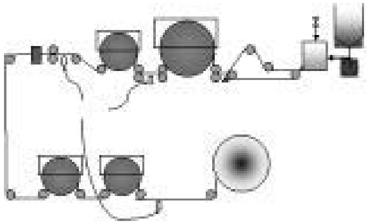
Control of Paper Machines

- Control Inputs (manipulated variables)
  - stock flow (solids), dryer temperatures (as set points to local PID loops), machine speed (as set point to drum motors)
- Process Outputs (controlled variables)
  - paper dry weight (~solids), Moisture content (at different points), machine speed (actual)
- Disturbances
  - Operators can change set-points in other loops to maintain the overall product quality. Feed consistency is a major disturbance, especially after paper breaks (re-circulation).



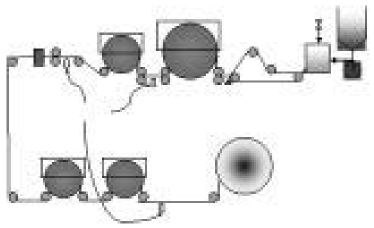
Control of Paper Machines

- Challenges in Paper Machine control
  - Consistency control (in the direction of production)
  - Cross-directional control (across the paper; distributed control, not discussed here)
  - Interacting variables, wide range of process responses. Standard decoupled single-loop control not very effective
  - E.g., Stock/Weight has long dead-time, short settling time, Steam/Moisture has short dead-time and long time constant, Machine Speed has minimal dead-time and fast dynamics. These features can have an adverse effect on both the identification and the robust control of a paper machine.



Control of Paper Machines

- Some ballpark numbers:
  - Total length of paper line ~500–1000m, speed 10–30 m/s (20–60 mi/h), dryer drums 2–3 m diam.
  - Sensors scan moisture and dry weight across the width of the paper. Scanning interval can be as large as 35 s.
  - Steam/moisture dynamics
    - ~temperature response of the drums (local PID control, closed-loop time constant in the order of a few minutes)
    - Short time-delays (scanners, drum-sensor distance), but larger delays for reel moisture (measured at the end of the line)
    - “Noise” from the interaction of the paper sheet with the environment



Control of Paper Machines

- Stock flow/dry weight dynamics
  - Larger delay since the actuator is located at the beginning of the line
  - Quick settling time, essentially determined by the stock mixing process
  - Any changes in the stock flow also have a significant effect on moisture, since it changes the net water content of the paper sheet
  - Changes in the drum temperatures or moisture leave the dry weight unaffected
- Machine speed
  - Can be controlled much faster than the other variables. Unaffected by steam or stock flow variations, but it has a significant effect on moisture and dry weight.

Heat Exchanger Control Example

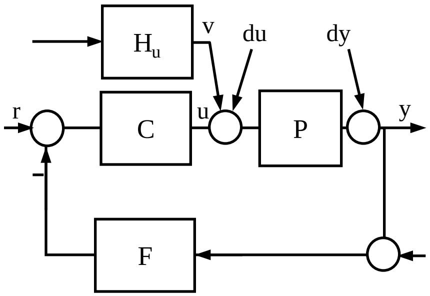
- Multivariable system (see textbook), both feedback and feedforward control
  - Measure inlet temperatures and water outlet temperature (controlled variable)
  - Manipulate steam inflow, water inflow through pneumatic valves
  - Water flow is a controlled variable, either to be maximized or to track a setpoint
  - Other valves and instruments to enable monitoring and ensure integrity

Plastic Injection Molding Process

- Multivariable system, approximating distributed sensing and actuation (see textbook)
  - Measure temperatures at different points
  - Apply heating power through SCR actuating modules at the same points
  - Accuracy is important

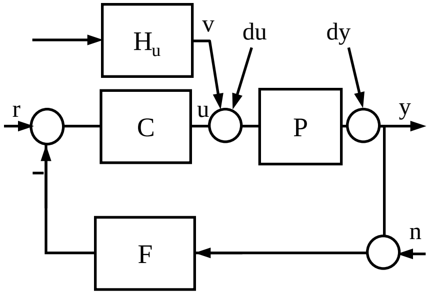
Other Control Examples

- Aerospace applications
  - high performance fighter aircraft, helicopters, jet engines
- Electromechanical systems
  - robotic arms, pendulum, cart and pendulum
- Automotive
  - intelligent vehicle highway systems, platooning, traffic control
  - engine management, anti-lock brakes, active suspension
- Manufacturing processes, scheduling of operations



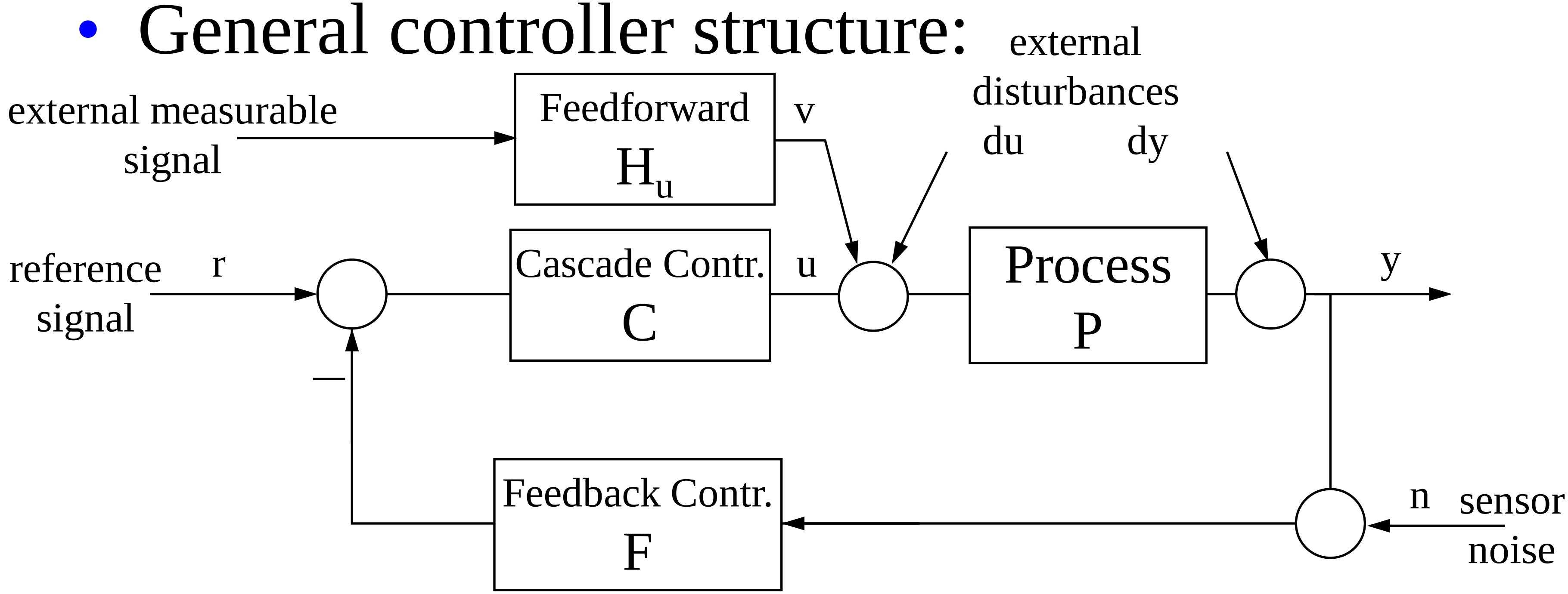
Feedback and Feedforward Control

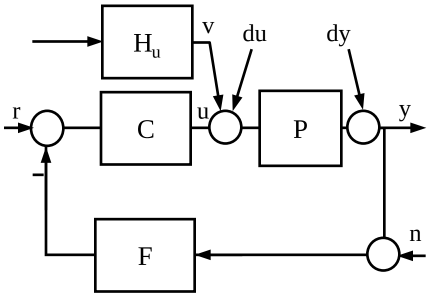
- Controller Design Procedure:
  - Determine inputs and outputs
  - Model or identify the system
  - Define the control objectives and specifications
  - Design the controller (algorithm and parameters)
  - Discretize (if working in continuous time), quantize and implement (code + hardware)
  - Anti-windups and other nonlinear modifications: integrated (recent methods) or “post-mortem”



Feedback and Feedforward Control

- On the controller design: computation of the transfer function(s) of the "controller"
- General controller structure:





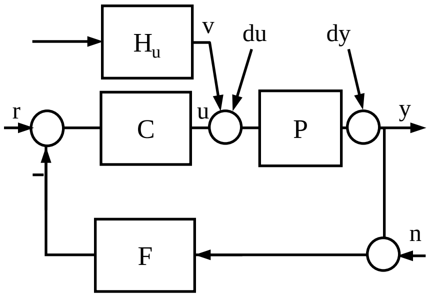
Feedback and Feedforward Control

- Feedback control objective: Reduce the effect of disturbances on the output

$$
\begin{aligned}
y &= d_y + P[u + d_u + v] \\
&= d_y + PC[r - F[y - n]] + Pd_u + Pv \\
&= Sd_y + SPCr - SPCFn + SPd_u + SPv
\end{aligned}
$$

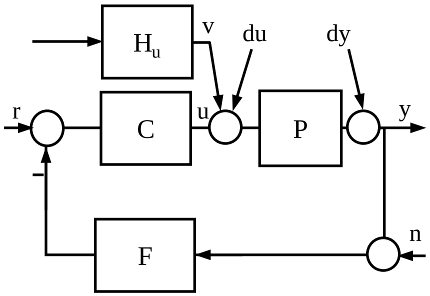
$$where\ S = (1 + PCF)^{-1}\ (Sensitivity)$$

  – the disturbance contributions decrease when S is smaller, i.e., when CF is larger
  – the noise contribution decreases when CF is smaller



Feedback and Feedforward Control

- Feedback controller design:
  - stable loop
    - PCF must produce a stable loop (crossover frequency characteristics)
  - large gain (magnitude) in the region where the sensor is reliable
    - in the same vein, respect uncertainty-imposed constraints (avoid excessive peaks/resonances in S)
    - can only attenuate disturbances where the sensor information is reliable

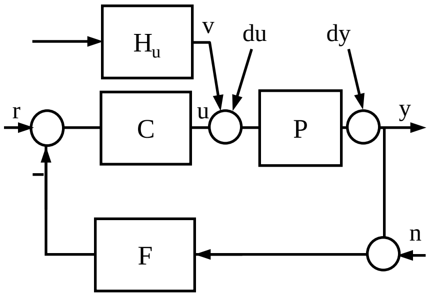


Feedback and Feedforward Control

- A typical feedback controller design (math):
  - frequency domain
  - observe fundamental limitations
    - RHP poles < bandwidth < RHP zeros
    - modeling uncertainty, sensor noise => max bandwidth
  - At the gain crossover frequency

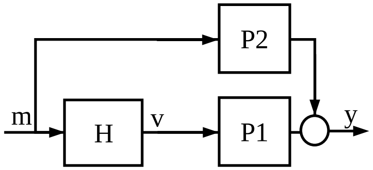
$$\omega_c : |PCF(j\omega_c)| = 1, \quad \angle PCF(j\omega_c) \approx -130 \pm 10^o$$

    - crossover separates the frequency range of high loop gain (disturbance attenuation) and low loop gain (sensor noise attenuation). Roughly, $BW \approx 1.5\omega_c$



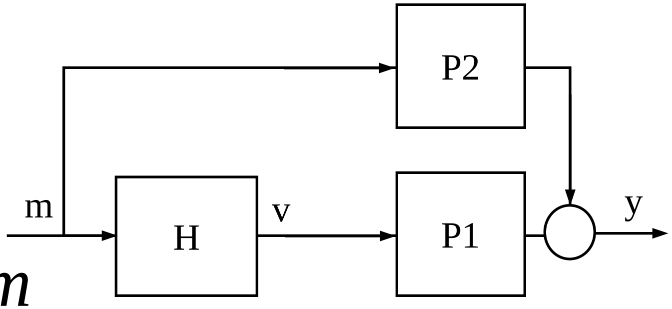
Feedback and Feedforward Control

- Feedback controller design:
  - Software automating most of the computations
    - Tuning of PID, robust multivariable, LPV…
    - Usually, concepts are understood in terms of transfer functions and in the frequency domain but the computations are performed in the state-space relying on time-domain optimal control theory
    - Here: simple PID tuning (Ziegler-Nichols, or pidqtune)
  - Still, the selection of reasonable objectives is essential



Feedback and Feedforward Control

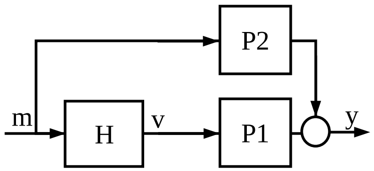
- Feedforward control objective: cancel the effect of a measurable disturbance at the output
  - General setting:



$$y = P_1 v + P_2 m = [P_1 H + P_2]m$$

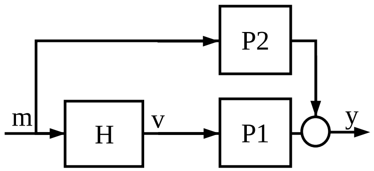
$$\Rightarrow \min \| P_1 H + P_2 \|$$

  - If P_1 were invertible, $H = -P_1^{-1} P_2$
    - Usually this is not the case



Feedback and Feedforward Control

- Typical feedforward controller design:
  - separate invertible (outer) and non-invertible (inner) parts: $P_1 = P_{1i} P_{1o}, \quad (P_{1i}^{\sim} P_{1i} = I)$
    - Inner-outer factorization for multivariable systems, by inspection in SISO. Inner: all-pass (unity magnitude)
  - Solve the associated minimization problem
    - "By inspection" in SISO. Easy in 2-norm minimizing error variance for gaussian inputs. More complicated in inf-norm minimizing error energy for energy inputs.
  - Invert or approximate the inverse of the outer part



Feedback and Feedforward Control

- Typical feedforward controller design (math)
  - inner-outer factorization $P_1 = P_{1i} P_{1o}, \quad (P_{1i}^{\sim} P_{1i} = I)$
  - minimization problem

$$\min \| P_1 H + P_2 \| = \min \| P_{1i} (P_{1o} H) + P_2 \| =$$

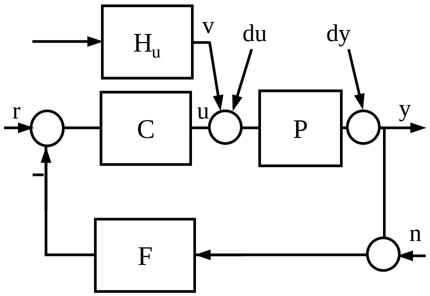
$$\min \| (P_{1o} H) + P_{1i}^{\sim} P_2 \| \quad (\text{since } P_{1i}^{\sim} P_{1i} = I \text{ and } \| P_{1i}^{\sim} \| = 1)$$

$$1. \| . \|_2 : H = (P_{1o})^{-1} (P_{1i}^{\sim} P_2)^{-} \ (\text{H2 - stable projection})$$

$$2. \| . \|_\infty : H = (P_{1o})^{-1} \{\arg \min_X \| X + P_{1i}^{\sim} P_2 \|_\infty \} \ (\text{Hinf - Nehari})$$

If P_{1o} strictly proper, $(P_{1o})^{-1}$ is not well defined

(then, approximate, add weights, or regularize)



Feedback and Feedforward Control

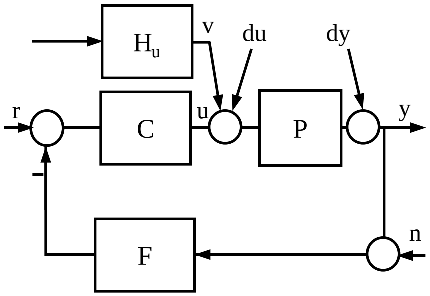
- Example of a (simplified) complete design:
  - Heating a tube of water, 10liters, 0.1m diameter.
  - Lumped model

$$mc_p\dot{T} = -hA(T - T_0) + q$$

$$y = T, \quad u = q, \quad d = T_0$$

$$y = \frac{hA}{mc_p s + hA} d + \frac{1}{mc_p s + hA} u$$

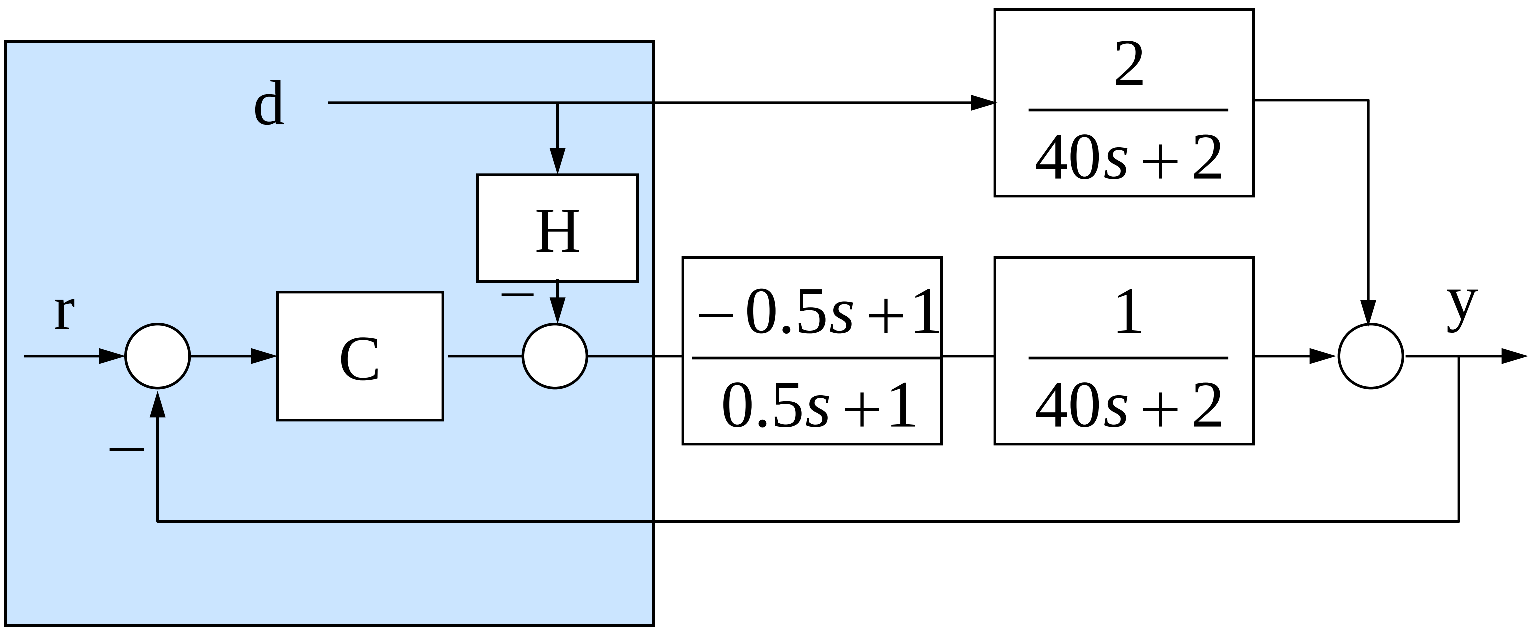
    - $mc_p \sim 40$, $h=5$, $A = \pi DL = 0.4$
  - Also, suppose that T_0 is measurable and there is a 1sec delay in applying the control input (u: q(t) = u(t-1)), modeled by a 1st ord. Pade approximation

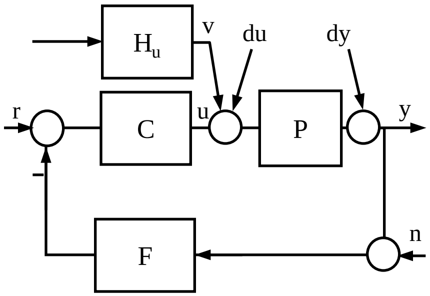


Feedback and Feedforward Control

- Model $$y = \underbrace{\frac{2}{40s+2}}_{Q} d + \underbrace{\frac{1}{40s+2}\,\frac{-0.5s+1}{0.5s+1}}_{P} u$$

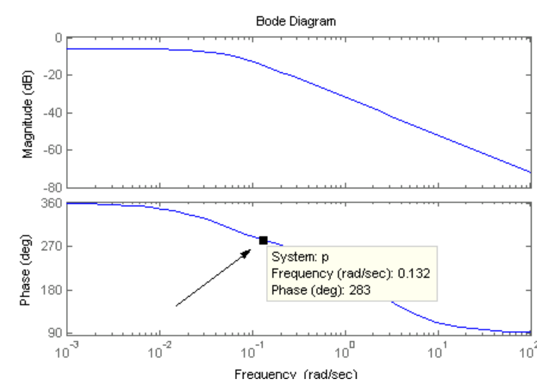
- Feedback-feedforward controller

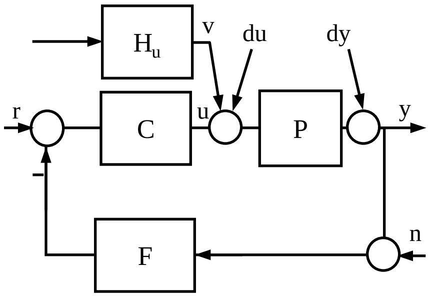




Feedback and Feedforward Control

- Feedback controller tuning:
  - Choose BW < 2, e.g., 0.2rad/s, (other design objectives and constraints would be included in this choice) => target crossover 0.2/1.5 = 0.133
  - Plant transfer function and frequency response
    - P=tf([-.5 1],[.5 1])*tf(1,[40 2])
    - bode(P)
  - phase at crossover: -77°



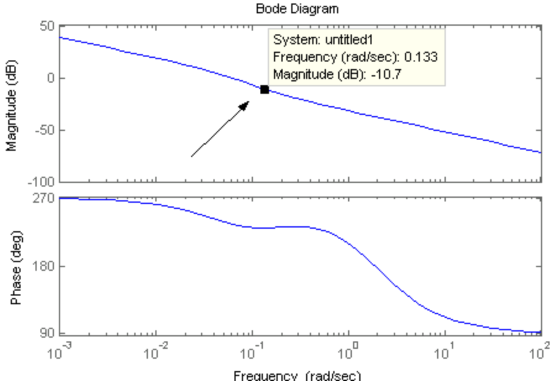


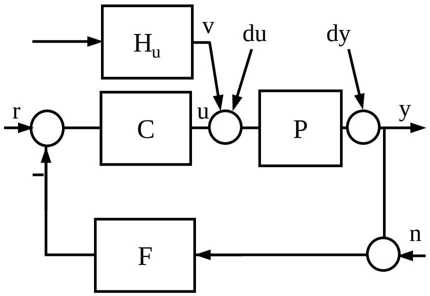
Feedback and Feedforward Control

- Feedback controller tuning:
  - PI controller: $C = K(s+a)/s$.
  - Adds phase at crossover: $\tan^{-1}(0.133/a) - 90^o$
  - For 50^o phase margin, $\tan^{-1}(0.133/a) = 37^o$

$$=> a = 0.1765$$

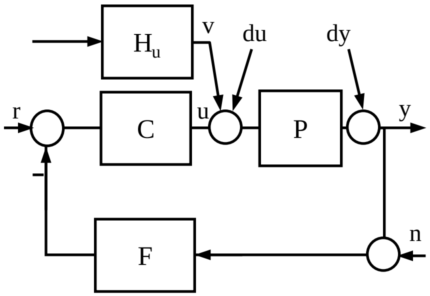
  - Find corresponding gain K:
    - C=tf([1 .1765],[1 0]); bode(P*C)
    - evaluate magnitude at 0.133
    - => K=3.43





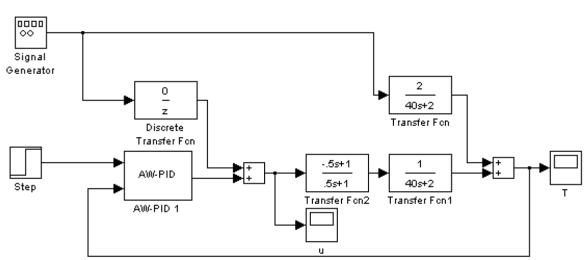
Feedback and Feedforward Control

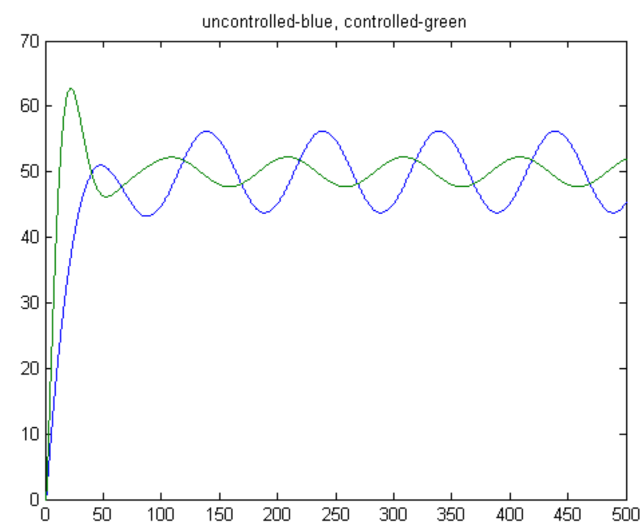
- Feedback controller tuning:
  - Final controller: C=tf([3.43 0.61],[1 0])
  - Check step response and bandwidth
  - step(feedback(P*C,1)) -> 23% overshoot
  - bode(feedback(P*C,1)) -> 0.2 rad/s bandwidth
  - sampling time < 1/0.2/10, (wT/2 < 0.1) say 0.1s
  - control signal limits 0-1000(W)

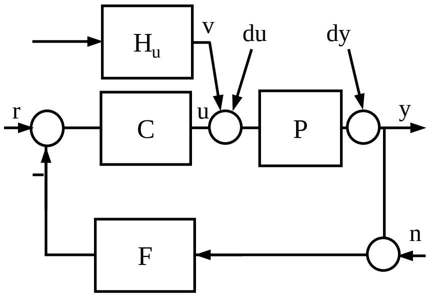


Feedback and Feedforward Control

- Feedback controller testing:
  - Test in Simulink
    - 50 deg. step. 10 deg., 0.01 Hz disturbance
  - PI controlled response vs. uncontrolled response
    - faster response
    - disturbance attenuation







Feedback and Feedforward Control

- Feedforward control
  - Develop expressions

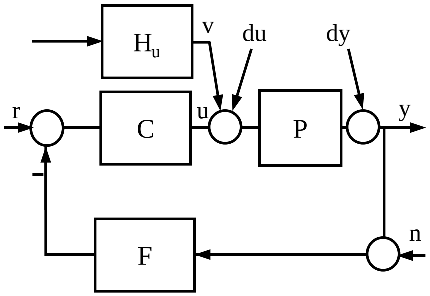
$$y = SPCr - SPHd + SQd \Rightarrow H : \min_H (\| SPH - SQ \|)$$

Subtract the feedforward signal to obtain the standard minimization problem

  - Frequency weighting and control penalty

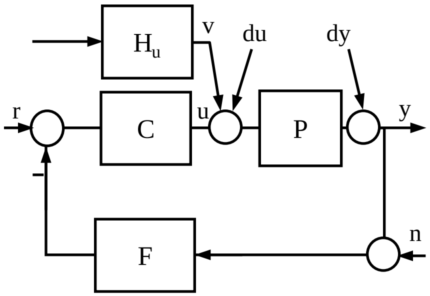
$$H : \min_H \left\| \begin{bmatrix} WSP \\ \rho I \end{bmatrix} H - \begin{bmatrix} WSQ \\ 0 \end{bmatrix} \right\|$$

  - W=tf([.5 1],[1 1e-4]); rho=1e-3 % This W improves low-frequency performance; the control penalty *rho* << 1, avoids ill-posed problems; larger values yield smoother controls



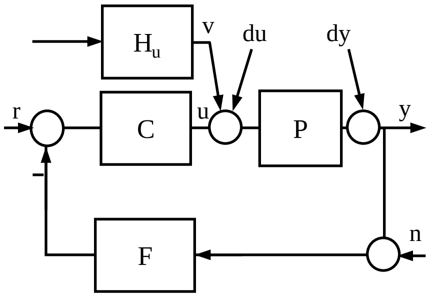
Feedback and Feedforward Control

- Feedforward control computations
  - S=feedback(1,P*C); SP=feedback(P,C); SQ=Q*S;
  - % Use the “feedback” function instead of just algebra
  - G=[W*SP;r]; WT=([W*SQ;0]);
  - [SPi,SPip,SPo]=iofr(ss(G)); Stil=inv([SPi,SPip]);
  - R=minreal(Stil*WT);
  - % Inner-outer factorization, minimal realization to keep system order low
  - X2=stabproj(R-R.d)+R.d; H2o=minreal(inv(SPo)*[1 0]*X2);
  - % Solve the associated net H-2 minimization problem but keep the throughput R.d in the stable part instead of splitting it (default in “stabproj”)



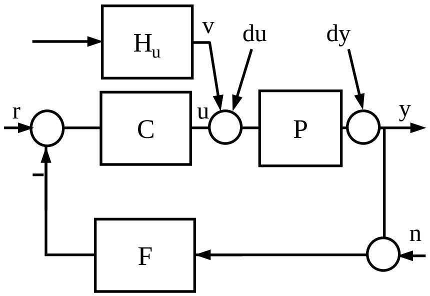
Feedback and Feedforward Control

- computations continued
  - cut=sum((abs(eig(H2o))<1e-2));
  - [H2s,H2f]=slowfast(H2o-H2o.d,cut);H2f=H2f+H2o.d;
  - [a,b,c,d]=h_sysred(H2f,[],[]); H2=ss(a,b,c,d);
  - % Perform model reduction (the price of generality). “slowfast” to remove irrelevant slow modes. “h_sysred” is a custom function, based on balanced truncation. Works with the old state-space format.
  - % Details in “Stability, Controllability, Observability notes,” http://www.fulton.asu.edu/~tsakalis/notes/sco.pdf



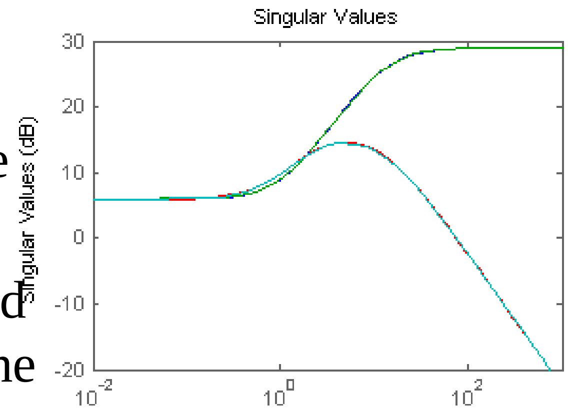
Feedback and Feedforward Control

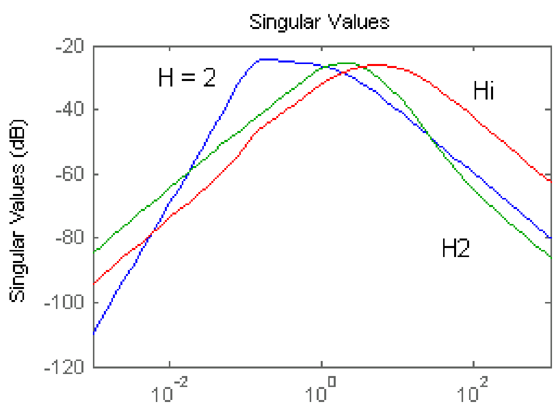
- H-inf computations
  - minimizes the worst case; but the solution is more complicated -the so called 2-block problem with gamma-iteration. “nehari” solves the H-inf problem; it is a custom program with the (older) state-space format.
  - gmax=norm(WT,inf); gmin=norm(R(2),inf);
  - while gmax-gmin>0.001
  - gam=(gmax+gmin)/2; r0=(sfl(minreal(R(2))/gam))*gam;
  - r1=minreal(R(1)*inv(r0));[a,b,c,d]=nehari(r1.a,r1.b,r1.c,r1.d,0);qm=ss(a,b,c,d);
  - q=minreal(inv(SPo)*qm*r0); gtest=norm((r(1)-qm)*inv(r0),inf);
  - if gtest < 1; gmax=gam; else gmin=gam;end
  - end
  - cut=length(find(abs(eig(q))<1e-2));[qs,qf]=slowfast(q-q.d,cut);qf=qf+q.d;
  - [a,b,c,d]=h_sysred(qf,[],[]); Hi=ss(a,b,c,d);

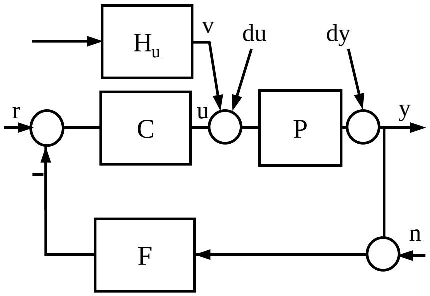


Feedback and Feedforward Control

- Controller Evaluation
  - Top Fig.: 2nd and full order feedforward filters are nearly the same
  - Bottom Fig.: Error transfer function for the 2nd and full order filters and the obvious choice (without the delay), H=2.
  - sigma(SP*2-SQ,SP*H2-SQ,SP*Hi-SQ)
  - The H-2/H-inf methods produce optimal results *systematically*
  - More pronounced differences for more difficult problems

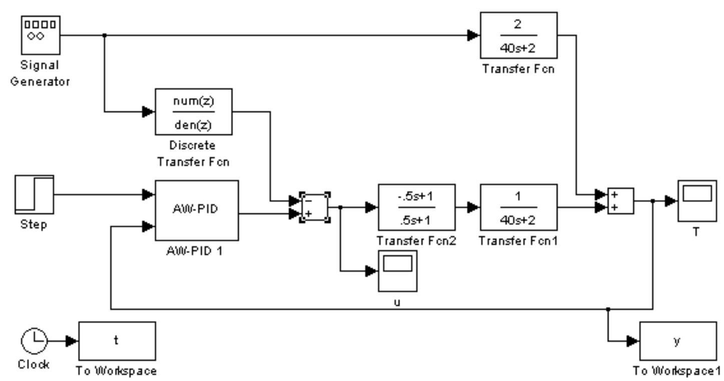


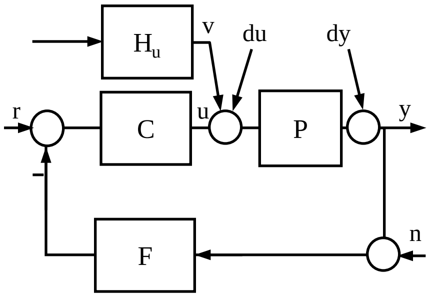




Feedback and Feedforward Control

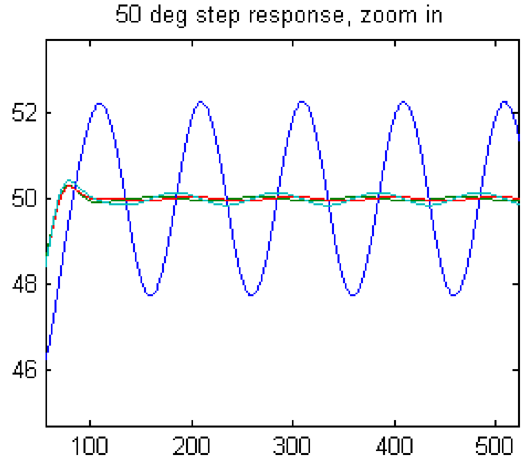
- Feedforward control implementation
  - Discretize the filter
    - [nu,de]=tfdata(bilin(H2,1,'bwdrec',.1),’v’)
    - [nu,de]=tfdata(c2d(H2,.1,’tustin’),’v’)
    - % use “bilin” with ‘bwdrec’ option or “c2d” with ‘tustin’
  - Introduce the filter in the Simulink model

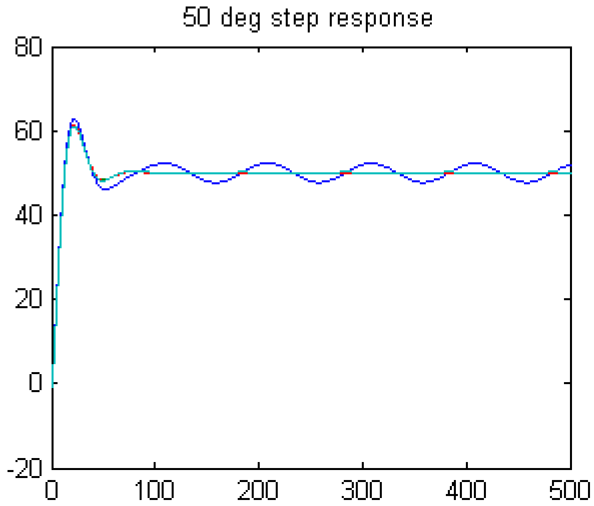


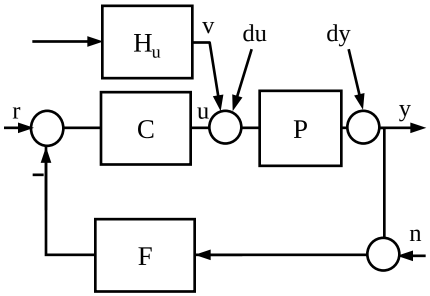


Feedback and Feedforward Control

- Feedback and Feedforward control testing
    - No feedforward (blue),
    - H2 solution (red),
    - Simple choice H=2 (cyan)

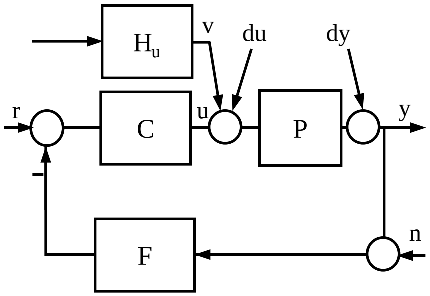






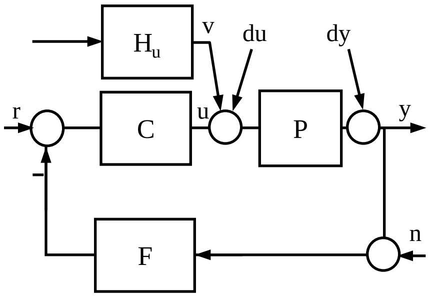
Feedback and Feedforward Control

- Feedback
  - Stabilizes or improves stability margin
  - Reduces sensitivity to unknown perturbations and model imprecision
  - Requires good sensors of process output
- Feedforward
  - Leaves sensitivity and stability unaffected
  - Provides faster corrections (than feedback)
  - Requires good models and good sensors of disturbance



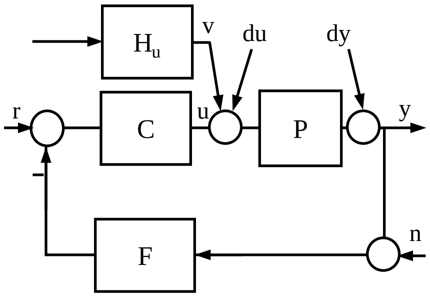
Feedback and Feedforward Control

- Other Design Methods
  - Feedback
    - Linear Quadratic Regulator (LQR) methods
    - General H2 and Hinf solutions to weighted sensitivity minimization (more complicated problem statement)
    - Model Predictive Control (MPC, on-line solution of an LQR optimization problem)
    - Other heuristic, optimization-based methods (e.g., PID)
  - Feedforward
    - Heuristic, algebraic
  - Discrete-time (sampled data) solutions



Feedback and Feedforward Control

- References
  - Anderson-Moore (LQR),
  - Zhou, Macejiowski (Hx, model reduction, feedforward),
  - Francis (Hx fundamentals),
  - McFarlane-Glover (Coprime factor methods)
  - Glad-Ljung (Linear/nonlinear/MPC… excellent survey)
  - Astrom (PID control)

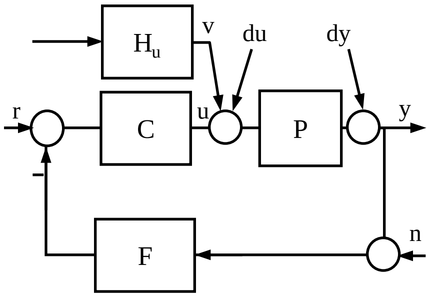


PID Control

- PID Tuning
  - PID is the industry workhorse

$$u = K_p e + K_i \int e + K_d \frac{de}{dt}$$

  - Proportional, Integral, and Derivative action to achieve all the basic feedback objectives: adjust bandwidth, introduce phase lead for stabilization, increase gain at low frequencies for disturbance attenuation



PID Control

- PID Tuning
  - Pseudo-differentiator: more realistic and avoids numerical problems in the design

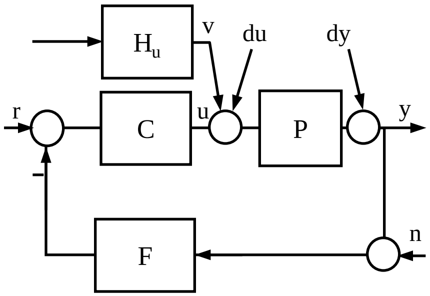
$$u = K_p e + K_i \int e + \frac{K_d}{T}(e - v)$$

$$T\dot{v} = -v + e$$

  - Transfer function:

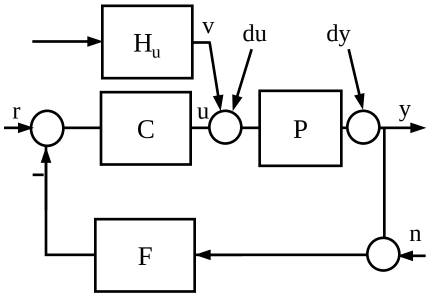
$$C(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{Ts + 1}$$

$$= \frac{(K_d + TK_p)s^2 + (K_p + TK_i)s + K_i}{s(Ts + 1)}$$



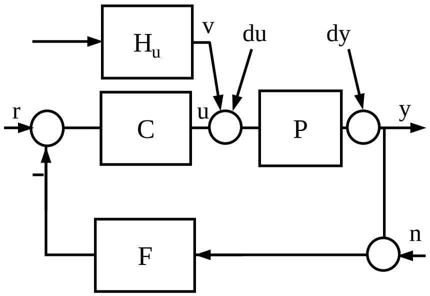
PID Control

- PID Tuning
  - Choosing *T*: minimum value is the sampling time for discrete implementation. It does not affect the design very much as long as 1/T > 10 BW
  - Tuning the PID: choosing the gain and the two zeros in the numerator (the num. is a 2nd degree, arbitrary polynomial, the den. is fixed)
    - Typically, the two zeros are chosen the same $PID = \frac{K(s+a)^2}{s(Ts+1)}$
    - PI: a special lag compensator $PI = \frac{K(s+a)}{s}$
    - PD: a lead compensator $PD = \frac{K(s+a)}{(Ts+1)}$



PID Control

- PID Tuning
  - Classical theory
    - phase margin at the intended crossover
  - Ziegler-Nichols
    - Practical methods based on simple models
  - Optimization and Loop-shaping
    - MATLAB custom function “pidqtune” minimizes the distance from a desirable target; target selected using LQR theory so that the closed loop is at least feasible
    - files in http://www.fulton.asu.edu/~tsakalis/notes



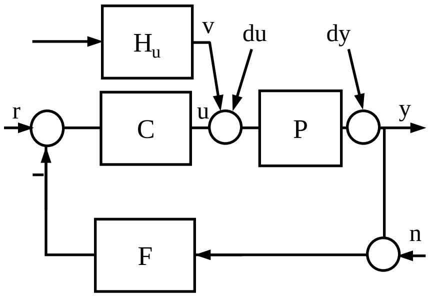
PID Control

- Ziegler-Nichols rules
- From step response data:
  - R = effective slope (e.g., 5%-15%)
    R~bandwidth
  - L = delay
- Experimentally, based on ultimate sensitivity:
  - Ku = ultimate gain
  - Pu = ultimate period.

Note: Z-N tunings are such that the ideal PID (with τ = 0) has a double zero, i.e., $Kp^2 = 4KiKd$.

1	P	PI	PID
Kp	1/RL	0.9/RL	1.2/RL
Ki	-	$0.27/RL^2$	$0.6/RL^2$
Kd	-	-	0.5/R

1	P	PI	PID
Kp	0.5Ku	0.45Ku	0.6Ku
Ki	-	0.54Ku/Pu	1.2Ku/Pu
Kd	-	-	0.075KuPu



PID Control

- PID Discrete Implementation

$$u_k = K_p e_k + K_i s_k + K_d (e_k - e_{k-1})$$

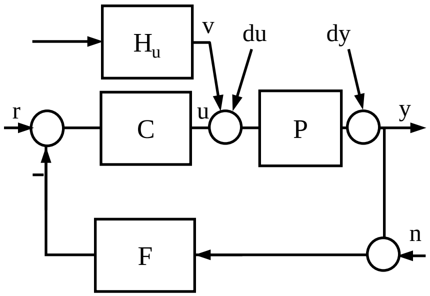
$$s_{k+1} = s_k + e_k$$

several different but equivalent implementation equations,

e.g., $\Delta u_k = u_{k+1} - u_k = \cdots$

– Integrator windup
  - Nonlinear behavior when the control input saturates (can lead to instability)
  - Remedy: Anti-windup modification (limited integrators)

$$s_{k+1} = \min[\max\{s_k + e_k, \tfrac{u_{\min}}{K_i}\}, \tfrac{u_{\max}}{K_i}]$$

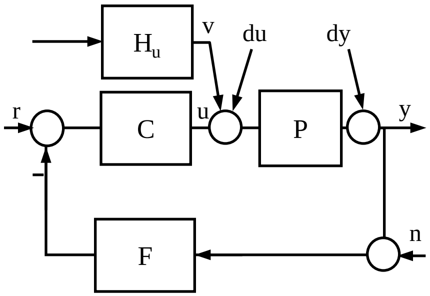


Controller Discretization

- Discretization

Continuous Time	Discrete Time
$\dot{x} = Ax + Bu$	$x_{k+1} = Ax_k + Bu_k$
$y = Cx + Du$	$y_k = Cx_k + Du_k$
$\frac{y(s)}{u(s)} = G(s) = D + C(sI - A)^{-1}B$	$\frac{y(z)}{u(z)} = G(z) = D + C(zI - A)^{-1}B$

  – MATLAB: “bilin” with ‘bwdrec’ (backward rectangular), ‘fwdrec’, ‘tustin’, etc.
  – “c2d” function for system objects, with ‘zoh’ (zero order hold) option, etc.



Controller Discretization

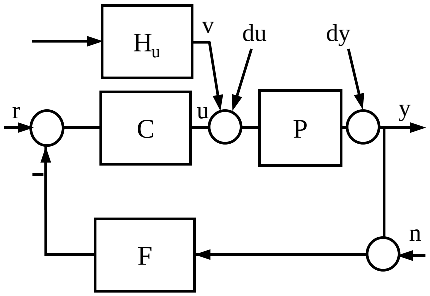
- Discretization derivations

$$\text{Forward Euler } \dot{x} = Ax + Bu \rightarrow \frac{x_{k+1} - x_k}{T} = Ax_k + Bu_k$$

$$G(z) = D + C[zI - (I + AT)]^{-1} TB$$

$$\text{Backward Euler } \dot{x} = Ax + Bu \rightarrow \frac{x_k - x_{k-1}}{T} = Ax_k + Bu_k$$

$$\begin{aligned} G(z) &= D + C[zI - (I - AT)^{-1}]^{-1} (I - AT)^{-1} TBz \\ &= D + C[zI - (I - AT)^{-1}]^{-1} \{z \pm (I - AT)^{-1}\} (I - AT)^{-1} TB \\ &= [D + C(I - AT)^{-1} TB] + C(I - AT)^{-1} [zI - (I - AT)^{-1}]^{-1} (I - AT)^{-1} TB \end{aligned}$$



Controller Discretization

- Discretization derivations

ZOH equivalent

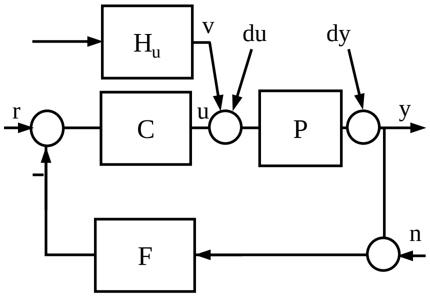
(sampled data response with piecewise constant inputs) :

$$\dot{x} = Ax + Bu \rightarrow x(t+T) = e^{AT}x(t) + \int_t^{t+T} e^{A(t+T-\tau)}Bu(\tau)d\tau$$

$$\rightarrow x_{k+1} = \{e^{AT}\}x_k + \{A^{-1}(e^{AT} - I)B\}u_k,\ y_k = Cx_k + Du_k$$

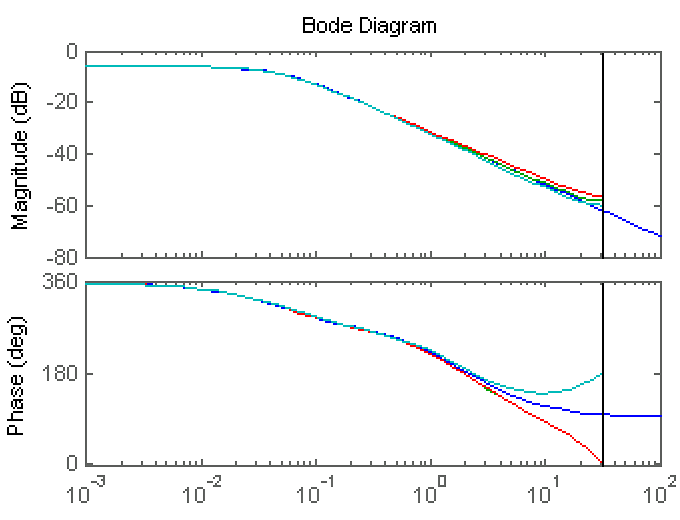
Tustin :

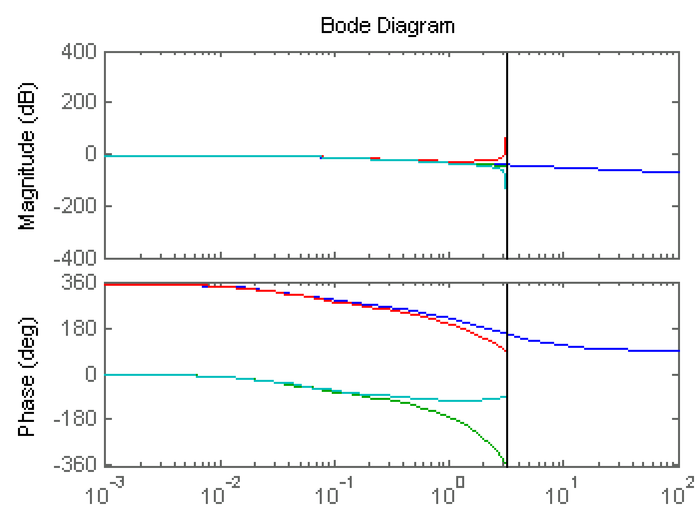
$$s = \frac{2}{T}\frac{z-1}{z+1}, \quad \left(z^{-1} = e^{-sT} \overbrace{=}^{Pade} \frac{1 - sT/2}{1 + sT/2} \Rightarrow s = \ldots \right)$$

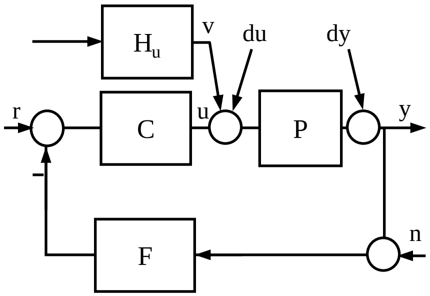


Controller Discretization

- Comparison of different discretizations
  - essentially the same results up to an order of magnitude below sampling rate (see bode plots below, Ts = 0.1, 1)
  - Slower sampling rates require either careful selection of discretization method or discrete design altogether

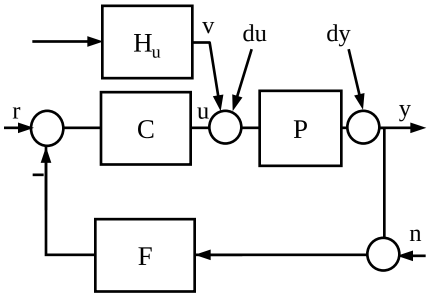






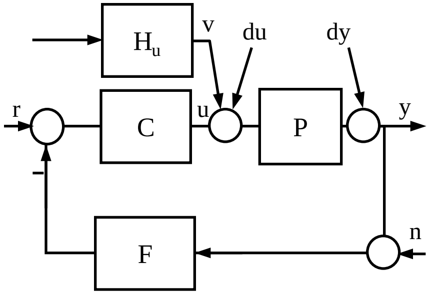
Controller Discretization

- Discretization comments
  - Continuous time design: done once, discretized easily for different sampling times (Ts) -by any method.
  - When approaching the sampling frequency, the discretized systems start deviating “unpredictably” from the continuous time frequency response and from each other
  - In such a case, there is no guarantee that a controller/filter will work as expected (e.g., discretizing a slow system with a slow sampling rate but asking for a very fast response)



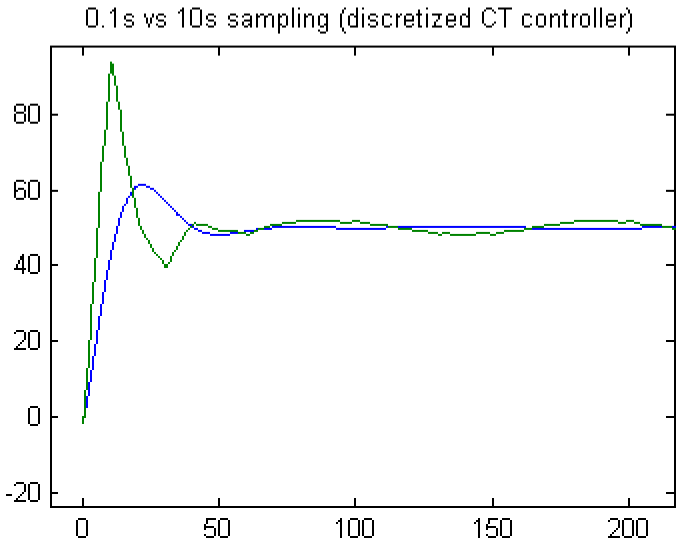
Controller Discretization

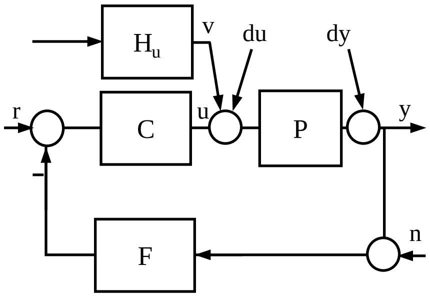
- Remedy: Obtain the ZOH equivalent response of the system and design a discrete controller/filter using the equivalent DT techniques (similar to CT but different computations)
- To illustrate the process, let us repeat the previous exercise (water tube) but with a 10sec sampling time
  - The system time constant is 20sec, so this discretization is somewhat adequate to describe the open loop. But the required closed-loop bandwidth is 0.2, (~5sec time constant) and therefore the sampling is too coarse to approximate the continuous time response.



Controller Discretization

– Using the previous (CT) design and discretizing the controller at 10sec, the closed-loop is unstable for ZOH and forward Euler discretization and stable for backward Euler; even for this, the response differs considerably from the continuous time design

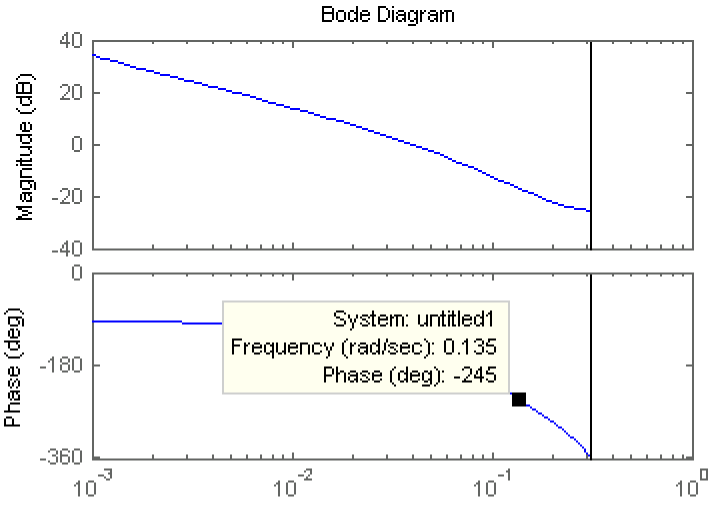




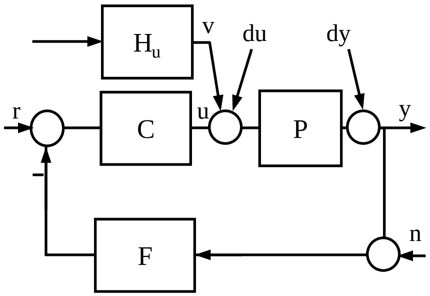
Controller Discretization

– Redesign the discrete PI(D) controller $K(z+a)/(z-1)$
– Pd = c2d(P,10) = (0.1812 z + 0.01555)/(z^2 - 0.6065 z)
– Let C = tf(1,[1 -1],10), and get bode(Pd*C)
– At crossover, phase = -245°
– Need 115° phase lead from *z+a*

$$a = \frac{\sin(0.133*10)}{\tan(115\pi/180)} - \cos(0.133*10)$$
$$= -0.6913$$

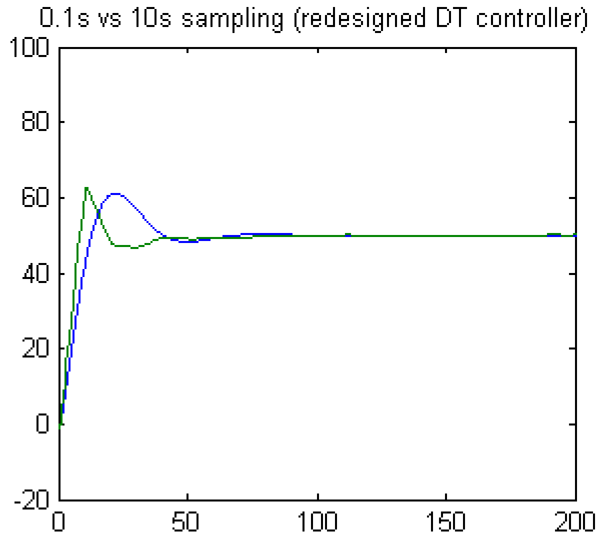


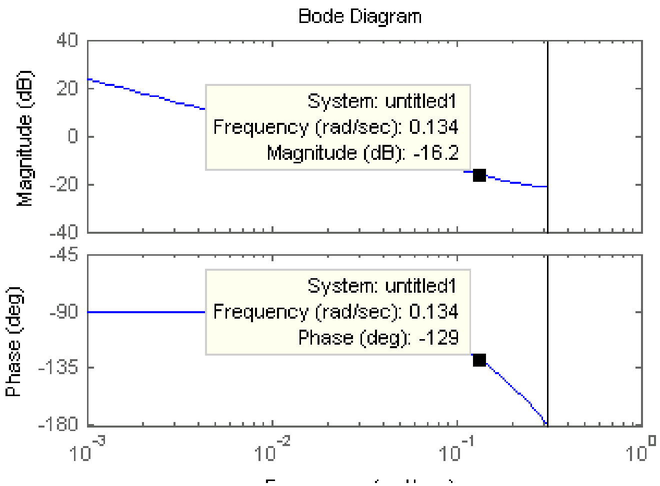
– Adjust C = tf([1 -.6913],[1 -1],10)
– and re-compute bode to find the gain K

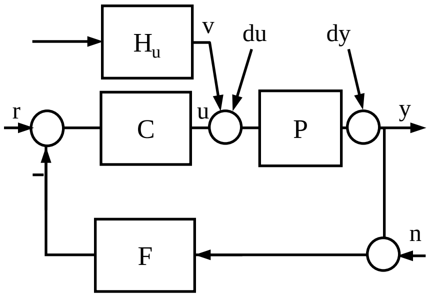


Controller Discretization

- We need K = 10^(16.2/20) = 6.456 to have 0.13 as the crossover frequency (with 50^o phase margin). So,
- C = tf(6.456*[1 -.6913],[1 -1],10)
- Good feedback performance!





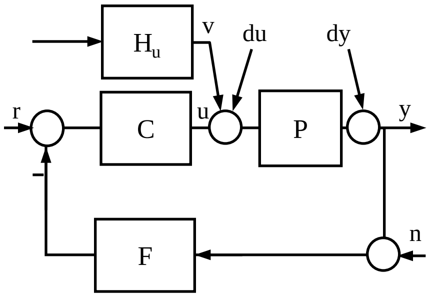


Controller Discretization (alt.)

- An alternative to the complete DT redesign is to adjust the CT PID for the phase lag of the ZOH at crossover (~ wT/2) and then discretize using the Tustin transformation to preserve the CT frequency response; the method works well as long as the crossover is well-below the Nyquist frequency.
- At crossover, the ZOH lag is approx. 0.665rad, or 38deg; design C for PM = 50+38 deg => C = (5.504 s + 0.1956)/s
- Discretize at 10 sec (Tustin) ; D = c2d(c1,10,'tustin') =>

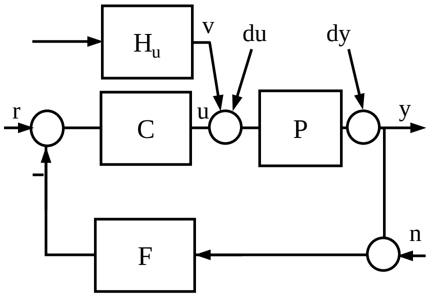
  D = (6.482 z - 4.526)/(z-1)

  (very close to the fully DT design)



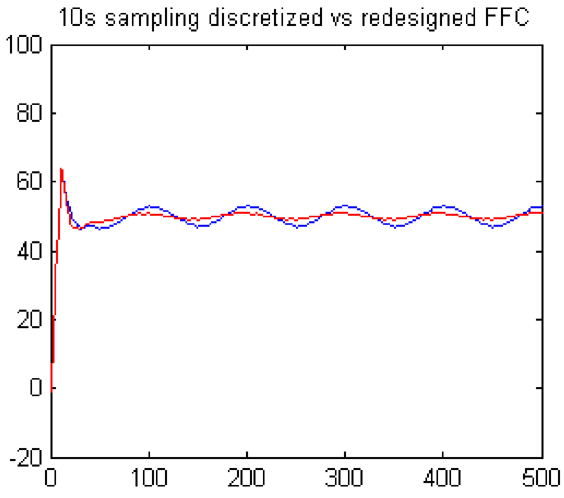
Controller Discretization

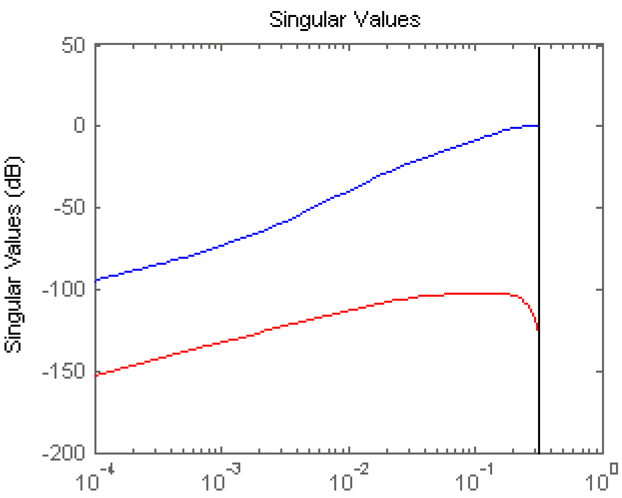
- Also need to redesign the FFC
  - The procedure is similar:
  - Discretize (ZOH equivalent) the plant model and form the various systems
  - Apply Tustin bilinear transform (norm preserving) to get a continuous-time equivalent problem
  - Solve for the FFC as before
  - Recover the discrete time solution by the inverse Tustin transform.

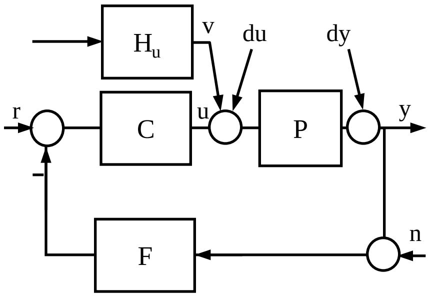


Controller Discretization

- DT-FFC results
  - The redesigned DT FFC response (blue) shows significant improvement over the 10sec discretization of the CT solution (blue)
  - But even though the error singular value plot is very small (red), the disturbance effect is not negligible…

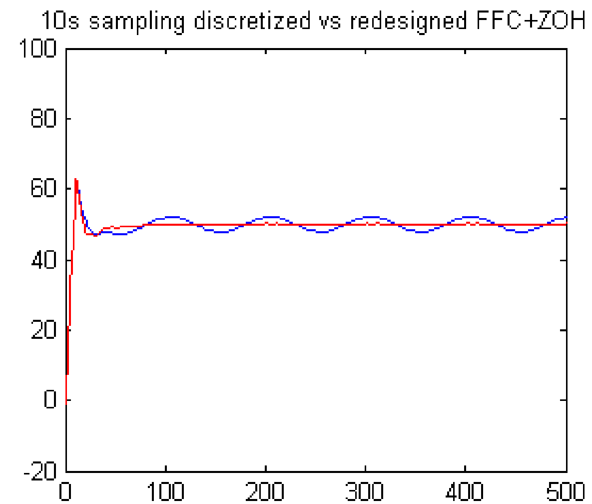






Controller Discretization

- DT-FFC results
  - The explanation is that the DT solution is accurate (no "unstable" zeros) but only for piecewise constant inputs in 10sec intervals. Our disturbance is a continuous sinusoid.
  - Indeed, when adding a ZOH after the disturbance source, the DT redesigned FFC works very well while the CT discretized does not.
  - Unfortunately real disturbances are not ZOH-sampled and lower sampling rates are detrimental to controller performance



Model Identification

- Parametric Model Identification from I/O data.
  - Non-parametric vs. Parametric models
  - Model parameterization: $y = P[u;\theta]$
  - Estimation error (to be minimized)
  - Batch/Recursive update equations
- For more details: Notes on adaptive algorithms, http://www.eas.asu.edu/~tsakalis/notes/ad_alg.pdf
- other bibliography: Ljung, Soderstrom-Stoica, Ioannou-Sun, Goodwin-Sin

Model Identification

- Data conditioning (pre-processing): avoid estimation of uninteresting effects
  - High frequency filtering
  - Offset and Drift removal (low-frequency filtering)
    - Justified by linearization principles
  - Scaling/conditioning
    - Numerical Sensitivity, uncertainty interpretations
    - Speed of convergence in recursive algorithms
- SNR and record-length issues

Model Identification

- Model parametrization

$$\dot{x} = Ax + Bu; \quad y = Cx + Du; \quad \theta = [A, B, C, D]$$

$$x_{k+1} = Ax_k + Bu_k; \quad y_k = Cx_k + Du_k; \quad \theta = [A, B, C, D]$$

$$y_{k+1} = b_n u_k + b_{n-1} u_{k-1} + \cdots + a_n y_k + a_{n-1} y_{k-1} + \cdots; \quad \theta = [b_n, \ldots a_n]$$

  - Models may include other external inputs such as noise, disturbances, effects of initial conditions (short data records/batch ID)
  - Parsimonious models: independent parameters, minimal parameter count. Identifiability
  - Persistent and Sufficient Excitation

Model Identification

- Parameter Estimation Objective
  - Estimation error formulation, equation error
  - $e = y - \phi^T\theta$; ϕ = regressor.
    - Linear-in-the-parameters (efficient algorithms exist)
    - Left factorization (observer), Coprime factor uncertainty
  - $e = y - P[u;\theta]$
    - Usually NonLinear-in-the-parameters
    - Additive uncertainty
  - …

Model Identification

- Parameter Estimation Methods
  - Least-squares, exponential weighting/fading memory
    - Fast recursive algorithms, Ellipsoidal parameter uncertainty
  - RMS (asymptotic)
    - Simple gradient algorithms, ultra-fast execution, slow convergence
  - Min-max (L-inf)
    - Linear programming algorithms, non recursive (except for sub-optimal approximations), Polytopic parameter uncertainty

Model Identification

- Estimation algorithms
  - Linear model estimation error $e_k = y_k - \phi_k^T \theta_k$

$$\text{Gradient}: \quad \theta_{k+1} = \theta_k + \frac{P\phi_k e_k}{1+\phi_k^T P \phi_k}, \quad P > 0$$

$$\text{Least-Squares}: \quad \begin{cases} P_{k+1} = \dfrac{1}{\lambda}\left[P_k - \dfrac{P_k \phi_k \phi_k^T P_k}{\lambda + \phi_k^T P_k \phi_k}\right], & 0 < \lambda \le 1 \\ \theta_{k+1} = \theta_k + P_{k+1}\phi_k e_k \end{cases}$$

  - λ: exponential weighting (forgetting factor). Typical values 0.990-0.999; depends on the number of parameters, excitation properties, parameter variations with time, etc.

Model Identification

- Estimation algorithms, Kalman Filter
  - Given the model

$$x_{k+1} = A_k x_k + v_k$$

$$y_k = C_k x_k + n_k$$

where, [v,n] is white noise with intensity diag(Q,R)

  - An optimal (min variance) estimate of the state x is

$$\hat{x}_{k+1} = A_k \hat{x}_k + L_k \left(y_k - C_k \hat{x}_k \right)$$

$$L_k = A_k P_k C_k^{\ T} (C_k P_k C_k^{\ T} + R)^{-1}$$

$$P_{k+1} = A_k P_k A_k^{\ T} + Q - A_k P_k C_k^{\ T} (C_k P_k C_k^{\ T} + R)^{-1} C_k P_k A_k^{\ T}$$

Model Identification

- Kalman Filter details
  - Assumptions: R>0, (A,C) observable, (A,Q) controllable
  - P-update: at steady-state becomes the discrete time filter algebraic Riccati equation. Its positive definite solution guarantees that (A-LC) is stable.
  - Returning to our estimation problem, write the linear model as a dynamical system $\theta_{k+1} = I\theta_k + v_k, \quad y_k = \phi_k{}^T \theta_k + n_k$
  - and apply KF

$$\hat{\theta}_{k+1} = \hat{\theta}_k + L_k\left(y_k - \phi_k{}^T \hat{\theta}_k\right), \quad L_k = P_k \phi_k (\phi_k{}^T P_k \phi_k + R)^{-1}$$

$$P_{k+1} = P_k + Q - P_k \phi_k (\phi_k{}^T P_k \phi_k + R)^{-1} \phi_k{}^T P_k$$

Model Identification

- Take R=1 (for a scalar output) and Q --> 0 to recover the standard LS updates
  - Some expressions may "look" different but they become identical after some algebraic manipulations
- Observability is equivalent to persistent excitation of ϕ
- The difference in implementation becomes important when adding constraints to parameters
- The KF handles parameter variations naturally through the noise term v and its covariance Q; if desired an exponentially weighted formulation can be derived to obtain the previous expressions; although it is not equivalent, the effect is similar

Model Identification

- An alternative algorithm for System Identification: Concatenate parameters and states into a big model (still linear but time-varying) and apply KF
  - this requires the system description in an observable form (left factorization); its generality is justified as follows:

$$
\begin{aligned}
x_{k+1} &= Ax_k + Bu_k \\
&= (A - LC)x_k + LCx_k + Bu_k \\
&= Fx_k + Ly_k + (B - LD)u_k \\
y_k &= Cx_k + Du_k
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
x_{k+1} &= Fx_k + \theta_1 y_k + \theta_2 u_k \\
y_k &= Cx_k + \theta_3 u_k
\end{aligned}
$$

  - F,C are design parameters: F should be stable and (F,C) should be observable

Model Identification

- Collect states and apply KF to estimate both states and parameters

$$\begin{bmatrix} x_{k+1} \\ \theta_{1,k+1} \\ \theta_{2,k+1} \\ \theta_{3,k+1} \end{bmatrix} = \begin{bmatrix} F & Iy_k & Iu_k & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{bmatrix} \begin{bmatrix} x_k \\ \theta_{1,k} \\ \theta_{2,k} \\ \theta_{3,k} \end{bmatrix}, \quad y_k = [C, 0, 0, u_k] \begin{bmatrix} x_k \\ \theta_{1,k} \\ \theta_{2,k} \\ \theta_{3,k} \end{bmatrix}$$

  - Notice that the model is nonlinear in the states and parameters but it becomes linear if the output is measured (and becomes an external time-varying parameter).
  - Drawback: output additive noise enters nonlinearly in this model
  - Choose Q_{11} >>Q_{22} (states vary much faster than parameters)
  - Convergence condition is again the persistence of excitation

Model Identification

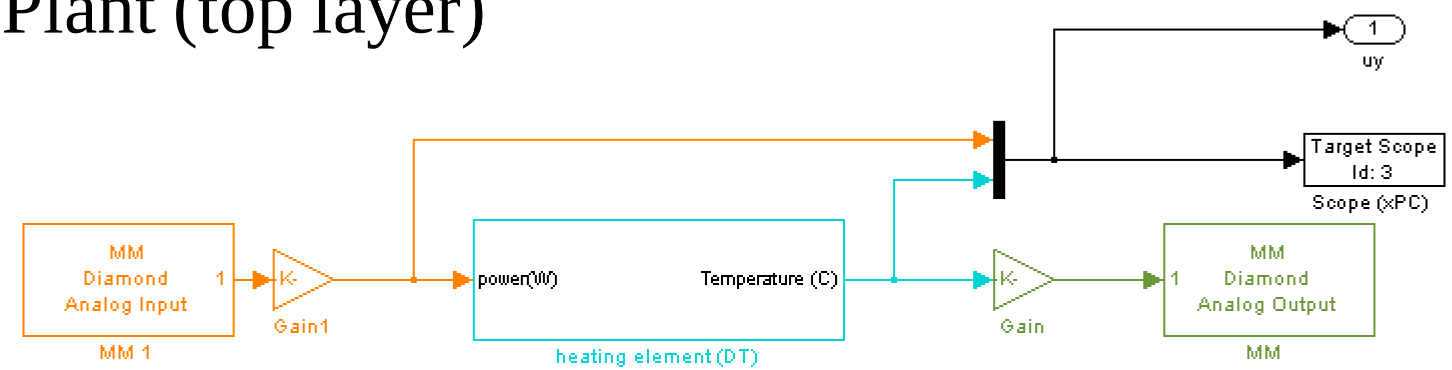
- Other Issues
  - Persistent excitation $\exists \delta, n > 0: \sum_{k=N}^{N+n} \phi_k \phi_k^T > \delta I > 0$, for all N
  - Possible parameter drifts in the absence of sufficient excitation (noise can mask the system)
    - Various modifications: Parameter projection, dead-zone, regularization noise, excitation monitoring
  - Modeling and estimation of dynamic uncertainty (region of model validity; analysis of residuals)

Model Identification

- Estimator modifications
  - Parameter projection
    - Knowledge of a convex set containing the parameters; find the best estimate in the set
  - Dead-zone
    - Do not update when the error is below the noise level
  - Regularization noise
    - Add artificial noise to the I/O pair used for estmation. Penalizes large estimates (~ min norm solution), ensures covariance boundedness, at the expense of a small bias
  - Excitation monitoring (high level logic)

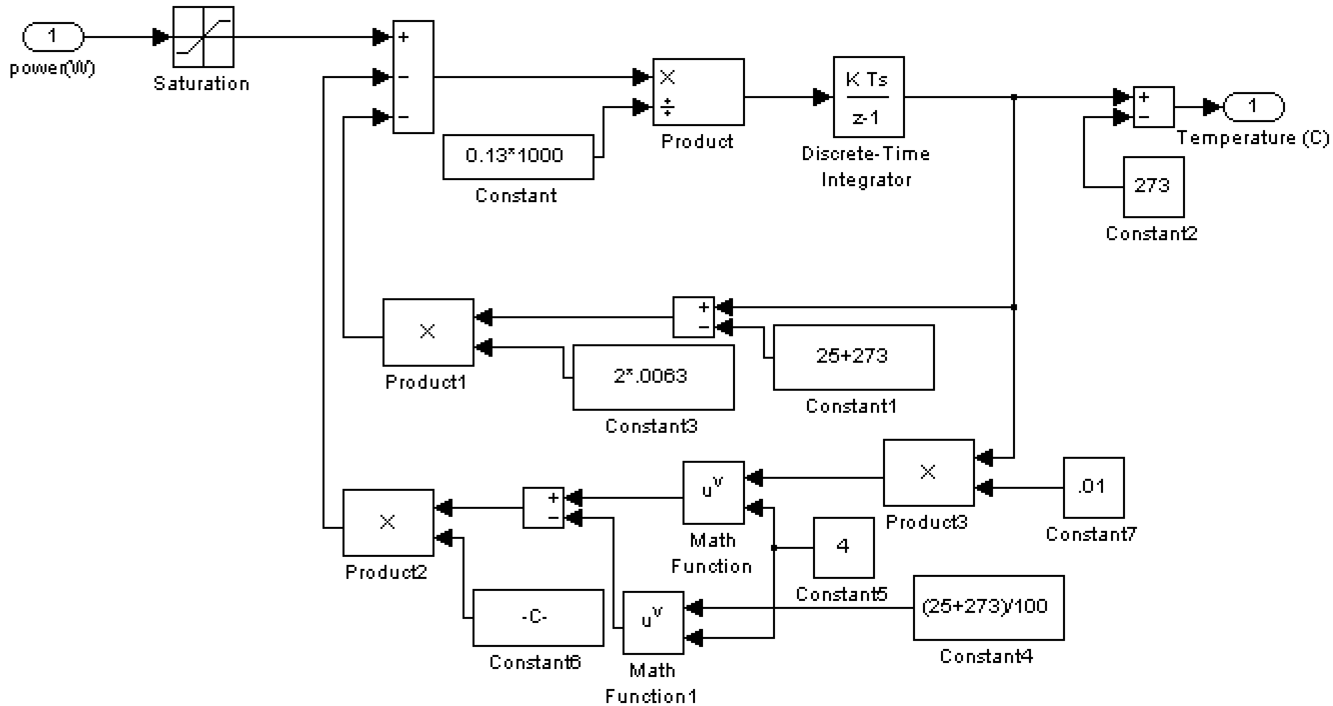
Model Identification

- Example
  - Temperature control of a heating element with on-line identification of its transfer function (Experiment 5)
  - Plant (top layer)



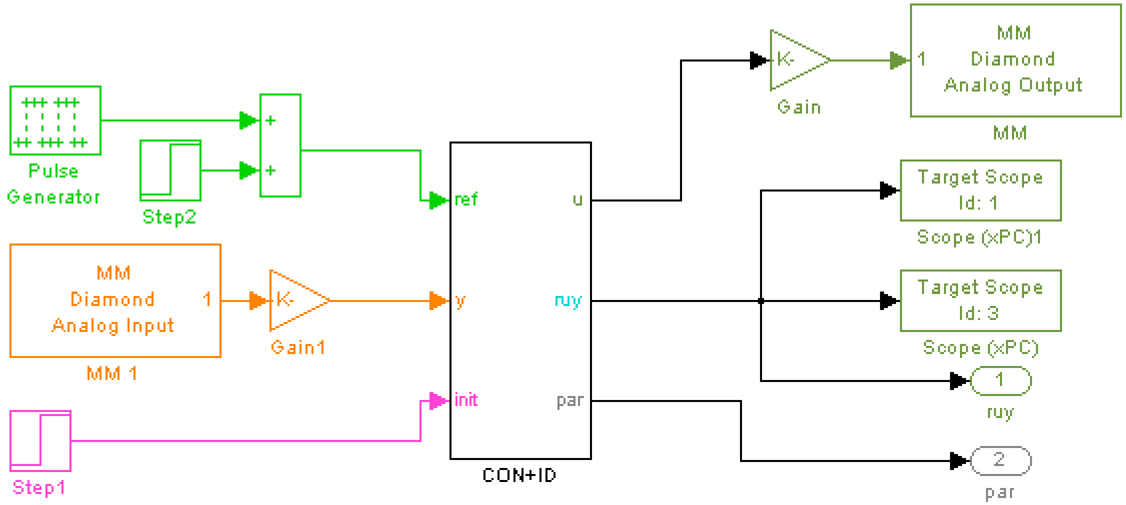
Model Identification

- Example
  - Plant model



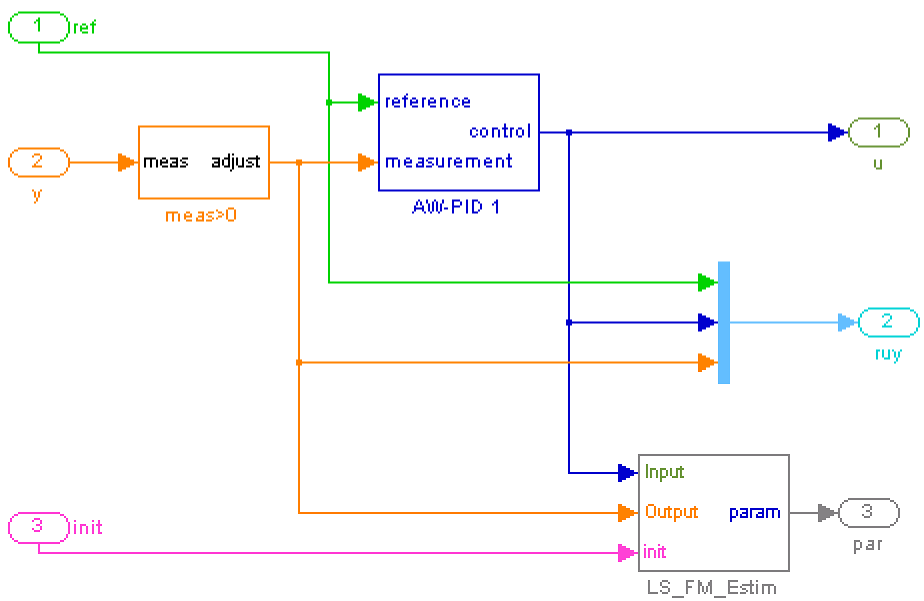
Model Identification

- Example
  - Controller (top layer)



Model Identification

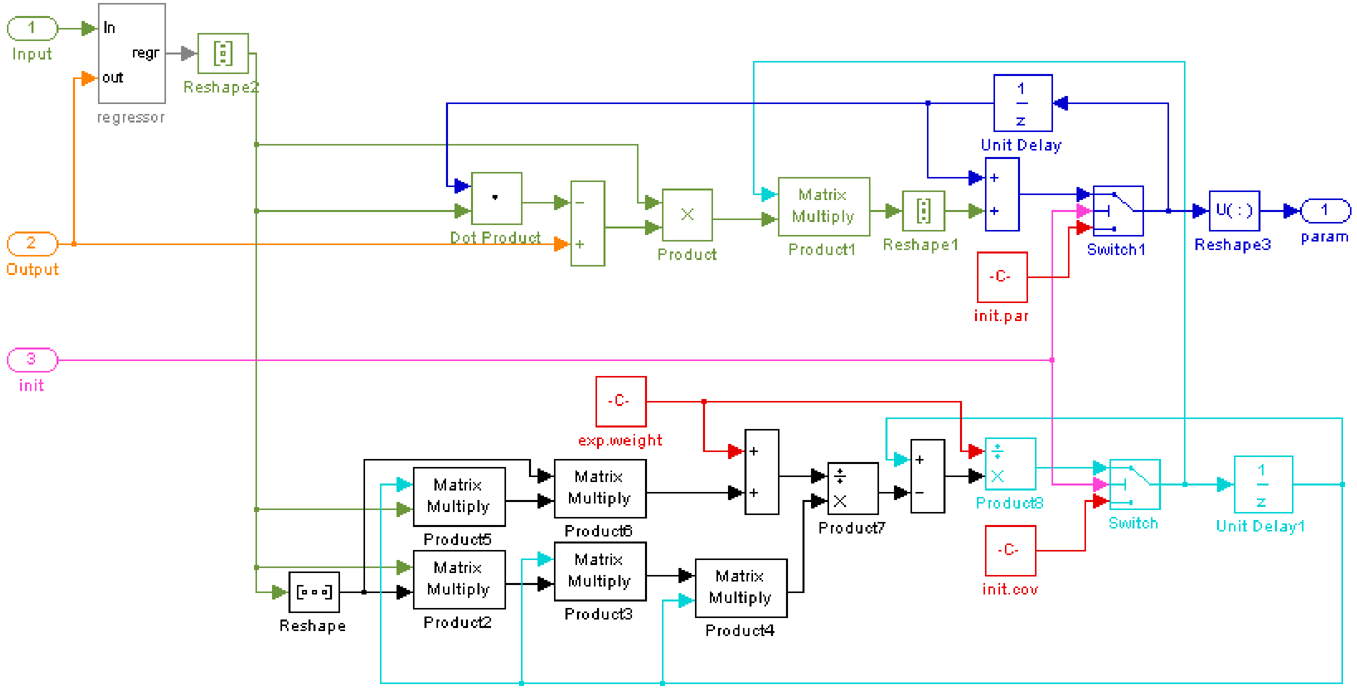
- Example
  - Controller block: PID, LSE



INITIALIZATION:
Tsa=.2;N=2;rho=1e3;lambda=.995;u_noise=1e-1;y_noise=1e0;

Model Identification

- Example
  - Fading Memory Least Squares Estimator



Model Identification

- Example
  - Experiment with different regularization noise levels, different estimators
    - LS parameter (textbook), LS/KF parameter (notes), KF parameter+state (notes)
  - Get familiar with the embedded function block and analyze the impact on execution speed
  - Try different model orders, add disturbances and monitor the excitation for different reference inputs…
  - Use prefilters on I/O data to remove nonlinear DC bias from linearization

Model Identification

- Example
  - Supplied functions:
    - Various estimator blocks (in idblocks)
    - Code to extract the state-space or transfer function model from the parameter vector in comments inside each block; remember to adjust the code when changing the model order or model structure
    - exp6KF.mdl contains a non-real-time version of the simulator to illustrate the operation of the parameter estimators

Instrument Ratings

- Usually static characteristics from manufacturers
  - Sensitivity: output magnitude to unit input
  - Dynamic range: upper-lower limits. Often expressed as a ratio in dB, usually range/resolution
  - Resolution: smallest change that can be detected
  - Linearity: maximum deviation from straight line
  - Zero/full scale drift: drift when input is maintained steady for a long period

Accuracy-Precision

- Errors can be deterministic (systematic) or random
  - Measurement accuracy = closeness of the measured value to the true value
  - Instrument accuracy = worst case accuracy within the dynamic range
  - Precision = reproducibility or repeatability
    - precision = measurement range/error variance
    - precision ~ measurement variance for constant input

Significance in measurement and computations

- Is a measurement 0.1V the same as 100mV? Or, is a resistance value 4.7kΩ = 4700Ω? What is the current flowing through a 3.3kΩ resistor when the voltage is 1.0V?
- Unless otherwise specified, the value is accurate to within 1 (or 1/2) least significant digit. So,
  - 0.1V = 0.1V +/- 0.1V
  - 100mV = 100mV +/- 1mV = 0.100V +/- 0.001V

Significance in measurement and computations

- In computations, the answer should have the same significant digits as the least of the numbers used in the calculation:
  - Current = Voltage / Resistance = (1.0 /3.3k)A = (0.3030…m)A = 0.30mA

from computation

  - Significant digits: digits past first nonzero digit

    1.0V/3300Ω = (0.0003030…)A = 0.00030A
  - **<u>Note</u>:** calculators compute with a fixed number of digits. Scientific notation is consistent with the significant digit concept.

Sensors and Actuators

- Sensors:
  - “Process Variable” to “Data” conversion
  - Change in certain material properties with changes in a process variable
  - Variety of sensor outputs: Electrical (potentiometers, thermocouples, thermistors, strain gauge), mechanical (bi-metallic thermometers), numeric (counters, optical sensors)

Examples of Sensors and Actuators

- Actuators:
  - “Data” to “Process manipulated variable” conversion
  - Variety of actuator inputs: Electrical (analog control circuits), numeric (computer control systems), pneumatic (some industrial controls)
  - Actuators/Final Control Elements: Heater (electric coil, gas burner, steam flow), Valve (pneumatic, solenoid, motor-driven), Light, Relay, Switch

Sensors

- Sensor Signal Conditioning
  - Convert signals to a form suitable for interfacing with the other elements of the process control loop
  - Digital form: advantages in computations, maintenance, reliability, cost
  - Typical operations: Amplification, Linearization, Filtering and Impedance Matching

Sensors: Signal Conditioning

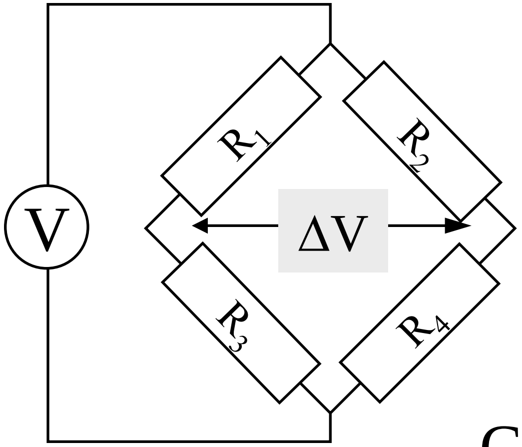
- Type of signal (variation/range) is usually fixed, depending on physical properties, (e.g., changes in resistance, voltage, etc).
- Amplification: Adjust the usually low signal level. Input impedance (transfer function) is important to assess speed of sensor response
- Linearization: Usually required; mild to severe nonlinearities; look-up tables and fitting functions; accuracy vs. precision

Sensors: Signal Conditioning

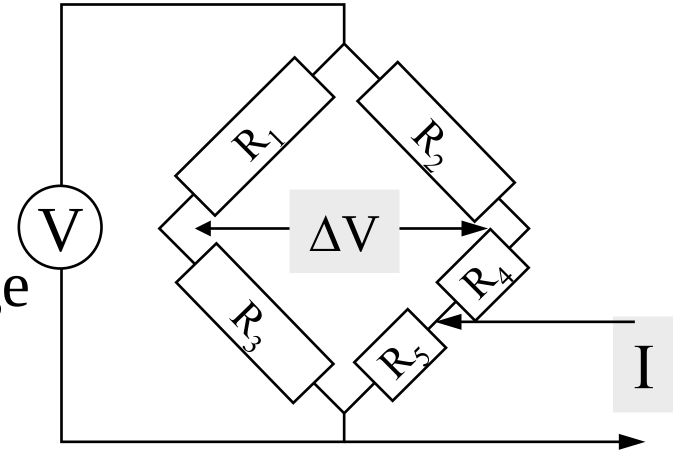
- Signal Conversion example: change in resistance to change in voltage or current
- Bridges to handle small fractional changes in resistance
- Analog Filtering to reduce aliasing effects.
- Impedance matching to improve dynamics and sensor signal strength (a power transfer problem)
- Active or passive filters; input impedance considerations

Sensors: Signal Conditioning

– Wheatstone bridge, current balance bridge: detection of a null condition (irrespective of voltage drifts)



$$\Delta V = V \frac{R_2 R_3 - R_1 R_4}{(R_1 + R_3)(R_2 + R_4)}$$



Current balance bridge

I s.t. $\Delta V = 0$

$R_4 >> R_5$

Thermal Sensors

- Thermal Energy ~ atom vibrations, atom speed
  - Average energy per molecule
  - Different Scales (K,C and R,F)
  - Thermal Energy of one molecule
    - 3/2 kT, k = 1.38 10^{-23} J/K (Boltzmann)
  - Average thermal speed $\sqrt{\frac{3kT}{m}}$
    - O_2, 90F, v = 488m/s
- Key sensor property: resistance vs Temperature

Thermal Sensors

- Metal resistance increases with temperature (more electron collisions).
  - Resistance Temperature Detector (RTD)
  - Pt: almost linear in [-100,600], repeatable, 0.004/^{o}C sensitivity.
  - Ni: nonlinear, less repeatable, 0.005/^{o}C sensitivity
  - measurement with a bridge
  - response: time for wire to acquire temperature
  - self heating effect from power supply (~1^{o}C)

Thermal Sensors

- Semiconductor resistance decreases with temperature (more free electrons): Thermistors
  - highly nonlinear resistance variation with temp.
  - effective range [-100,300] ^{o}C
  - Insensitive at high temperatures
  - 0.5-10s response time (depending on sensor mass and environment)
  - encapsulation material issues

Thermal Sensors

- Thermocouples: thermo-electric effect in a junction of different metals, voltage generation vs. temperature
  - Require cold junction reference
  - Almost linear; linearization tables for accuracy
  - Good range, sensitivity, inertness
  - Type J: [-200,700]^{o}C, 0.05mV/^{o}C, max 43mV
  - Type K: [-190,1260]^{o}C, max 55mV
  - Type R: [0,1482]^{o}C, 0.006mV/^{o}C, max 15mV

Thermal Sensors

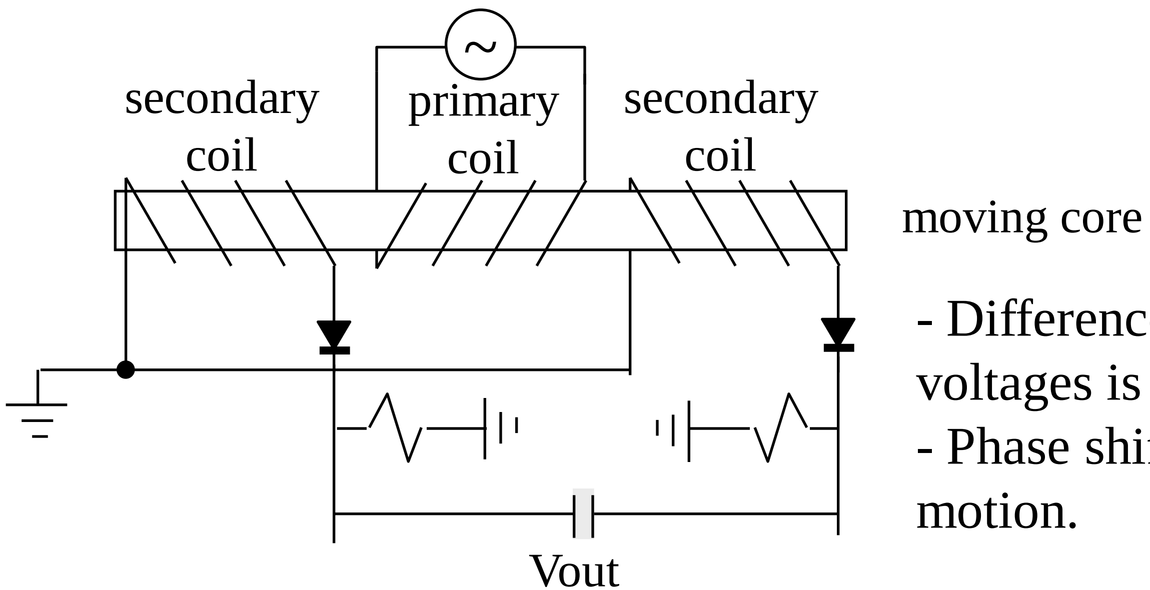
- Thermocouple signal conditioning
  - x100 amplification, susceptible to electrical noise and E/M interference
    - twisted wires, grounded sheath, grounded junction
    - Reference compensation circuits with precision thermistors
- Bimetallic strips (volume expansion)
- Gas thermometer (sensitive but slow)
  - vapor pressure, liquid expansion, solid-state
- Pyrometers (more details in optical sensor section)

Position-Motion Sensors

- Displacement-location-position
  - Ex. liquid level, object position/orientation, infer pressure
  - Potentiometers: resistance and wiper
    - wear, friction, resolution, noise; but linear and simple
  - Capacitance: $C = K\varepsilon_0 A/d$
    - ex. movement of one plate changes area; measurement with an AC bridge
  - Inductance: Armature moving through a coil

Position-Motion Sensors

- LVDT: Linear Variable Differential Transformer
  - Key component of many sensors
  - 2um resolution in commercially available systems



- Difference in secondary coil voltages is linear with displacement.
- Phase shift indicates direction of motion.

Position-Motion Sensors

- Level sensors
  - Float with a secondary displacement measuring system (e.g., LVDT)
  - Based on capacitance or conductivity properties of the fluid
  - Ultrasonic non-contact sensor (measuring reflection time)
  - Pressure-based sensor

Position-Motion Sensors

- Motion types
  - rectilinear motion (v,a), ~10g acceleration
  - angular motion (rotation)
  - vibration, ~100g, cos wt -> w^2cos wt
  - shock (impact), ~500g
- Motion sensors
  - Accelerometers (mass-spring)
  - Natural frequency $f_N = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

Position-Motion Sensors: accelerometers

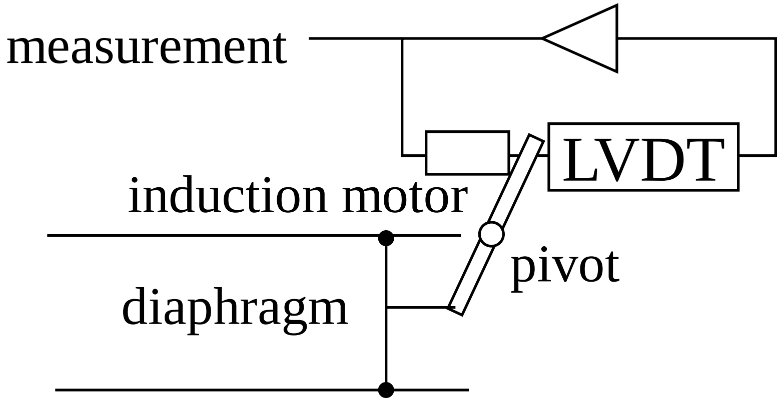
  - $f < f_N/2.5$: f_N has little effect on response
  - $f > 2.5\ f_N$: response independent of applied frequency; a vibration measurement; the “seismic mass” remains roughly stationary
- Potentiometric accelerometers: ~30g, steady-state acceleration, low frequency vibrations
- LVDT: 80Hz, Variable reluctance (LVDT-like), 100Hz, vibration only, geophones
- Piezoelectric: 2kHz, shock and vibration apps.

Pressure Sensors

- Pressure basics
  - F/A, units Pa, psi, Atm, bar. (1bar ~ 1atm ~ 100kPa ~ 14.7psi)
  - Static pressure (no flow).
  - Dynamic pressure (flow-dependent)
  - Gauge pressure (p_{abs} - p_{atm})
  - Head pressure (ρgh, static)

Pressure Sensors

- Pressure sensors, >1atm
  - with diaphragm or bellows, and LVDT sensor
  - Bourdon tube
  - electronic conversion



Pressure Sensors

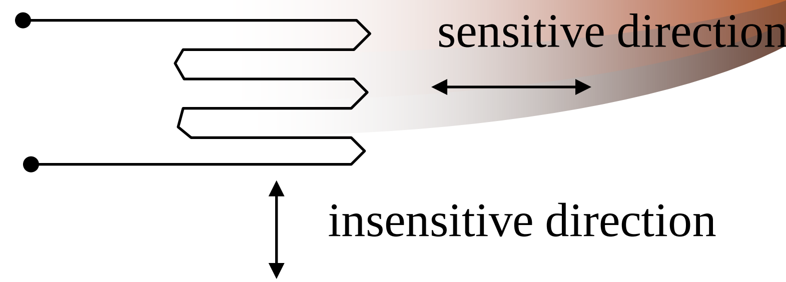
- Pressure sensors, <1atm (electronic)
  - Pirani gauge. Filament temperature via resistance measurement or thermocouple-based; nonlinear pressure dependence); 10^{-3}atm, calibrated for the type of gas.
  - Ionization gauge 10^{-3}- 10^{-13}atm
    - heated filament - electrons - ionized gas - current between electrodes
    - approximately linear

Strain Sensors

- Stress = F/A; tensile, compressional, shear
- Strain = $\Delta l/l$; tensile, compressional, shear
- Modulus of elasticity (Young) E = stress/strain
  – linear for low stress, elastic region
- Strain gauge: resistance change ~ strain
  – order of 0.1% fractional change
  – temperature compensation necessary (temperature effects are more significant)

Strain Sensors

- Wire/foil gauges
- Semiconductor gauges



- Gauge Factor = $\dfrac{\Delta R / R}{strain}$
  - 2 - 10 for metals
  - (-5) - (-200) for semiconductors but nonlinear
- Applications
  - load cells for large weight measurement (~500tons)
  - force sensors for nonlinear feedback in robotics

Flow Sensors

- Conveyor belt
  - load cell with strain gauge: measure weight on a fixed length of belt; belt speed is given/measured
- Liquid (volume or mass flow)
  - restriction (Venturi, orifice plate, nozzle) $Q \sim k\sqrt{\Delta p}$
  - obstruction: rotameter (liquid/gas), moving vane (angle~flow), turbine (tachometer~flow)
  - magnetic, (conductors/insulated pipe): flow through a magnetic field and measure the transverse potential

Optical Sensors

- EM radiation spectrum

Band	Frequency	Wavelength $c = \lambda f$
VLF	MHz	300m
TV/radio	MHz-GHz	0.3m
Microwave	THz	0.3mm
Infrared	10^{15}Hz	0.3um
Visible		400-760nm
UV	10^{17}Hz	3nm

Optical Sensors

- Photo detectors
  - spectral response (wavelengths)
  - time-constant, response time
  - detectivity
- Photo conductive detectors
  - semiconductor conductivity (or resistance) as a function of radiation intensity
  - resistance drops as number of absorbed photons with higher energy than band gap increases

Optical Sensors

– temperature control is important since it affects resistance

Photo-conductor	time constant	spectral band
CdS	100ms	0.47-0.71u
CdSe	10ms	0.6-0.77u
PbS	400us	1-3u
PbSe	10us	1.5-4u

Optical Sensors

- Photo Voltaic detectors
  - "giant diodes", $V = V_o \log(I)$
  - time-constants: Si (20us), Se (2ms), Ge (50us), InAs (1us)
  - photodiode detectors (changes in I-V characteristics): 1us - 1ns response time (for communication apps)
  - photoemissive detectors: current ~ light intensity, photo-multipliers, very sensitive

Optical Sensors

- Pyrometers
  - Temperature ~ emitted EM radiation; black body radiation ~ T^4 (total)
  - Broadband pyrometers, total radiation pyrometers
    - micro-thermocouple on blackened Pt disc; heats up with radiation and thermocouple generates a voltage; responds to all wavelengths
  - IR pyrometer (Si-Ge)

Optical Sensors

- Pyrometer applications
  - Metal production, glass production, semiconductors
  - range 0-1000^{o}C
  - accuracy 0.5-5^{o}C
  - noninvasive
  - Correction factors
  - Contamination issues (viewport fogging)

Optical Sensors

- Optical light sources
  - conventional: incandescent, atomic (distributed, divergent, incoherent, polychromatic)
  - Laser (monochromatic, coherent, non-divergent)

He-Ne	red	0.5-100mW (cont)	ranging alignment, comm.
Ar	green	0.1-5W (cont)	heat, small welding, comm.
CO_2	IR	1-100kW (cont-pulse)	cutting, welding, drilling, comm.
Ruby	red	1GW (pulse)	cutting, welding, drilling, comm.

Optical Sensors

- Incremental Optical encoders
  - Identical, equally spaced transparent windows
  - Two photodiodes, quarter pitch apart (to establish direction).
  - Angle of rotation is the summation of pulse counts (rising edge).
  - Velocity is window spacing by elapsed time.
  - Resolution is: $\Delta\theta = \frac{2\pi}{N}, \Delta\omega = \frac{2\pi}{NT}$ N = windows, T = sampling time
  - e.g., 10,000 windows => 0.018^{o} resolution

Optical Sensors

- Absolute Optical encoders
  - Code pattern on the encoder disk
  - N tracks to provide 2^N resolution (N ~ 14), each track associated with a pick-off sensor
  - Gray coding: one bit switching between adjacent sectors; minimizes errors due to manufacturing tolerances (e.g., eccentricity)

Actuators and Final Control Elements

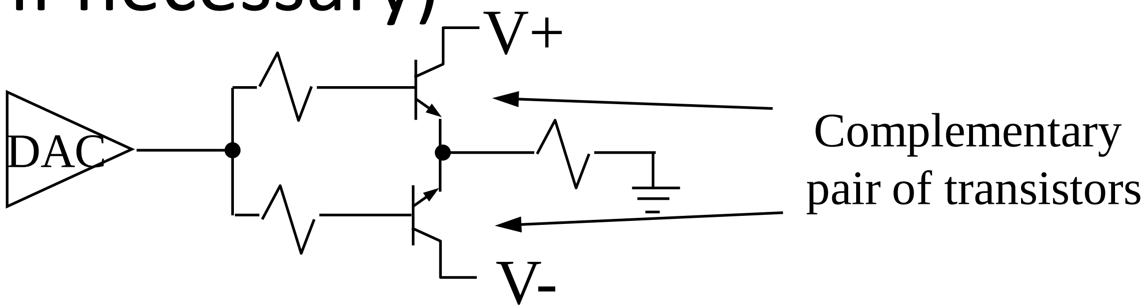
- Implementing changes in process variables
  - Relays, SCR/TRIAC (motor and heater control)
  - Amplifiers (Analog, PWM)
  - Solenoids (electromechanical conversion)
    - coil and plunger; free standing or spring loaded
  - Motors
    - DC: series field (hi-torque, difficult speed control); shunt (lower torque, easy speed control); compound
    - AC (Synchronous-Asynchronous, Low starting torque)
    - Stepping

Actuators and Final Control Elements

- Pneumatic signals: pressure as information carrier
  - 3-15psi standard , 330m/s propagation (sound)
- Amplifiers (diaphragm-based), Hydraulics
  - Nozzle-Flapper (mechanical-pneumatic conversion)
  - Diaphragm-Spring (pneumatic-mechanical conversion)
  - Current-2-Pressure conversion (solenoid-nozzle-flapper)
- Valves (Quick open, Linear, Equal Percentage)
- Hopper valves (solids), Rollers

Actuators

- Push-pull class B amplifier. (Use multiple stages, if necessary)

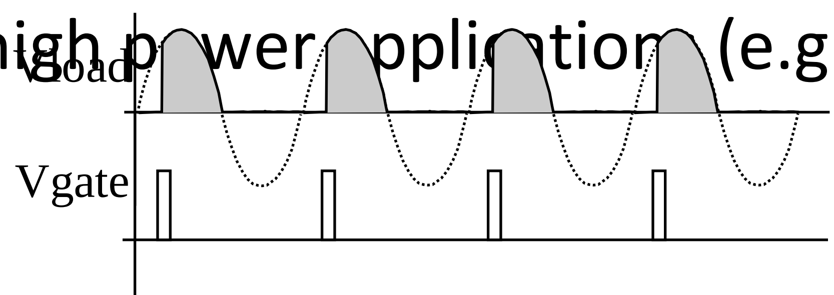


- Pulse Width Modulated (PWM) amplifiers
  - Varying the duty cycle of a square wave
  - Efficient switching transistors for high power requirements

Actuators

- Silicon-Controlled Rectifier (SCR, thyristor)
  - trigger voltage at the gate will start conducting positive voltages from anode to cathode; it will stop when the forward bias at the gate is off and the anode voltage is negative (half-wave operation)
  - TRIAC: full-wave operation
  - Power Control for high power applications (e.g., heating)

SCR
half-wave
operation



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