458.308 Process Control & Design

Lecture 5: Feedback Control System

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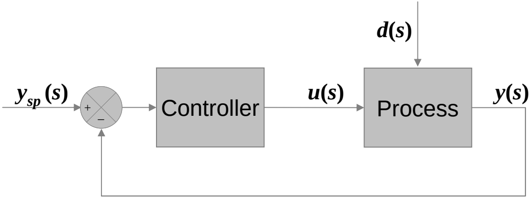
Feedback Control Scheme: The Continuous Blending Process

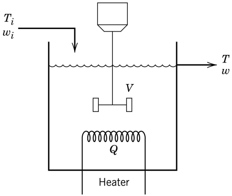
1. Sensor (AT) measures the controlled variable: x.
2. Controller (AC) calculates the manipulated input: w_2 in terms of an electronic signal.
3. Current-to-pressure (I/P) converts it to an equivalent pneumatic signal.

Simplified Control Block Diagram



- Negative feedback: self-stabilizing property with positive process gain
  - $e = y_{sp} - y$
- Positive feedback: makes a process unstable with positive process gain in general
  - $e = y_{sp} + y$
  - Used for describing complex systems (i.e., biological system)

Block Diagram



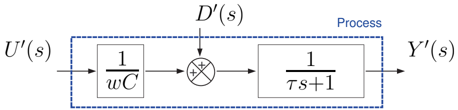
- See lecture 2 for mass, energy balance eqns.
- $w_i = w$: No need for mass balance

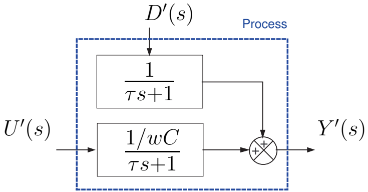
$$\frac{dT}{dt} = \frac{w_i}{V\rho}(T_i - T) + \frac{Q}{\rho V C}$$
$$\Rightarrow \tau \frac{dT}{dt} = (T_i - T) + \frac{Q}{Cw}$$

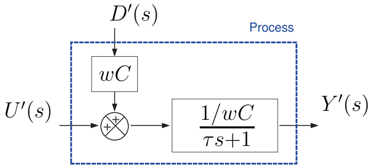
$$y' = T - \bar{T},\ u' = Q - \bar{Q},\ d' = T_i - \bar{T}_i$$

$$Y'(s) = \frac{1}{\tau s + 1}\left(\frac{U'(s)}{Cw} + D'(s)\right)$$

Equivalent Representations







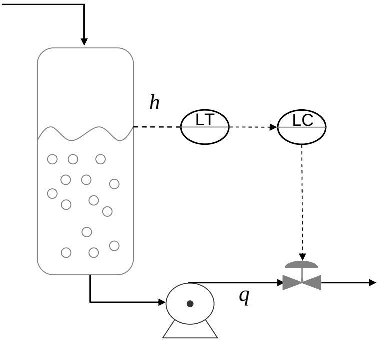
Proportional Control

Adjustment proportional to the current error

$$p(t) = \bar{p} + K_c(y_{sp}(t) - y_m(t)) \quad \Rightarrow \quad p'(t) = K_c e(t)$$

- Static control, memory-less control
- Proportional Band (PB) = $\frac{100}{K_c}\%$ (Foxboro, etc.)
- Reverse acting vs. Direct acting (Read section 8.3.2 in the textbook.)
  - Reverse acting: sensor output (y_m) $\uparrow \Rightarrow$ Controller output $\downarrow \Rightarrow K_c > 0$
  - Direct acting: sensor output (y_m) $\uparrow \Rightarrow$ Controller output $\uparrow \Rightarrow K_c < 0$

Level Controller (LC): Reverse-Acting or Direct-Acting?



- Level transmitter (LT): designed to be direct-acting (most transmitters are direct-acting)
  - Its output signal increases as the level increases.
- Air-to-Open Valve: direct-acting
- Air-to-Close Valve: reverse-acting

P-Controller: Advantages and Disadvantages

- Advantage: simplicity
- Disadvantage
  - Leaves offset with a set-point change or a sustained disturbance.

    Note: $\bar{p}$ is a equilibrium point (input) for the ``previous" set point or disturbance.

Proportional Integral (PI) Control

Adjustment proportional to the current error + accumulated error

$$p(t) = \bar{p} + K_c \left(e(t) + \frac{1}{\tau_I} \int_0^t e(t^*)\,dt^* \right)$$

- τ_I: Integral time or Reset time ($\to \infty$=P-control)

- Integral control action: reset control, floating control
- Some variations
  - Honeywell: $p(t) = \bar{p} + K_c \left(e(t) + \tau_R \int_0^t e(t^*)\,dt^* \right)$
  - Foxboro: $p(t) = \bar{p} + \frac{100}{PB} \left(e(t) + \tau_R \int_0^t e(t^*)\,dt^* \right)$
  - τ_R: reset rate

PI-Controller: Advantages and Disadvantages

- Advantage: eliminates offset (regardless of size of K_c)
- Disadvantage
  - One more parameter to tune
  - Easier to induce oscillation or instability

Proportional Integral Derivative (PID) Control

Adjustment proportional to the current error + accumulated error + current rate of change in the error

$$p(t) = \bar{p} + K_c \left(e(t) + \frac{1}{\tau_I} \int_0^t e(t^*) dt^* + \tau_D \frac{de}{dt} \right)$$

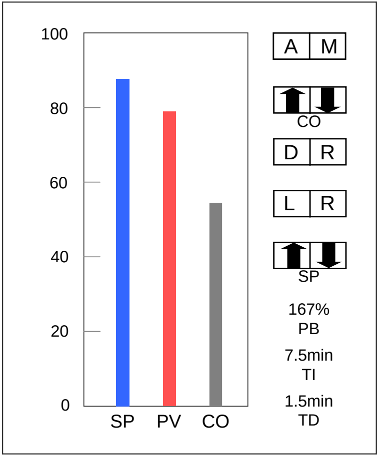
- τ_D: Derivative time constant

- Pure differentiation in real-time is not possible since evaluation of de/dt at time t requires error information beyond time t. But it can be approximated very closely.

PID-Controller: Advantages and Disadvantages

- Advantages
  - Quick action to a change in the error -- effective prevention of runaway (e.g., in an auto-catalytic reactor)
  - Decrease settling time for processes with slow dynamics and fast disturbances
  - Decrease oscillation (stabilizing factor for integral mode, etc.)
- Disadvantage
  - Yet one more parameter to tune
  - Amplifies measurement noise effect (not suitable in flow control)

Typical PID Controller Display



- PV, SP, CO: Process variable, Set point, Control output (normalized 0--100%)
- Local/Remote Switch: source of set point signal
- Auto/Manual Switch: Auto $\leftrightarrow$ Manual (Bumpless transfer)
- Direct/Reverse Switch

Digital PID Controller

Analog:

$$p(t) = \bar{p} + K_c \left(e(t) + \frac{1}{\tau_I} \int_0^t e(t^*)\,dt^* + \tau_D \frac{de}{dt} \right)$$

Digital:

$$p(t_k) = \bar{p} + K_c \left(e(t_k) + \frac{\Delta t}{\tau_I} \sum_{i=0}^{k} e(t_i) + \tau_D \frac{e(t_k) - e(t_{k-1})}{\Delta t} \right)$$

- Δt: sampling period (interval)
- $e(t_k)$: error at the k^{th} sample time
- $p(t_k)$: controller output at the k^{th} sample time

Removing ``Kicks"

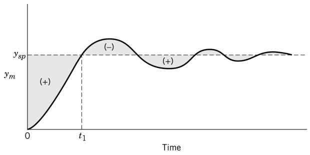
- Sudden set point change (a step change)
  - de/dt will be very large, giving a sudden jump in the valve position (undesirable in most cases)
  - Apply the derivative action only on the output signal, not set point signal

$$\frac{de}{dt} = \frac{d}{dt}\left(y_{sp}(t) - y_m(t)\right) \Rightarrow -\frac{dy_m}{dt}$$

- Similar phenomenon can show up for the P-mode, though not as severe as the D-mode

Windup and Anti-Windup

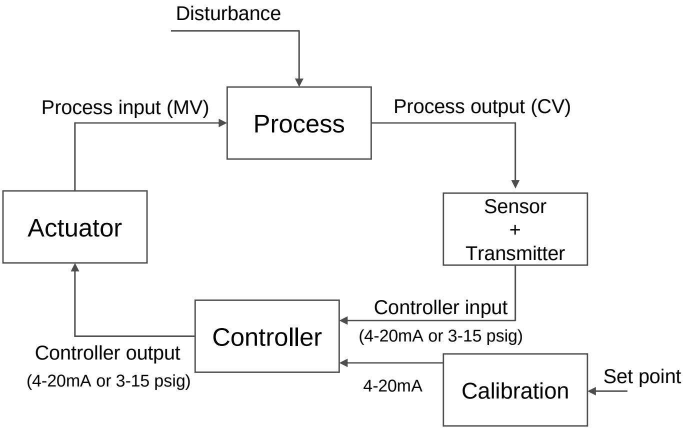
- Windup
  - When a constant error persists for a long time (such as when the valve ``saturates"), the integral term can be wound up to a very large term
- Consequence
  - When the reason for the constant error (e.g., un-realizable set point change or too large a disturbance to reject completely) goes away, the integral term must unwind before the valve position returns to the normal value and control resumes.
  - Large error in the opposite direction will result.



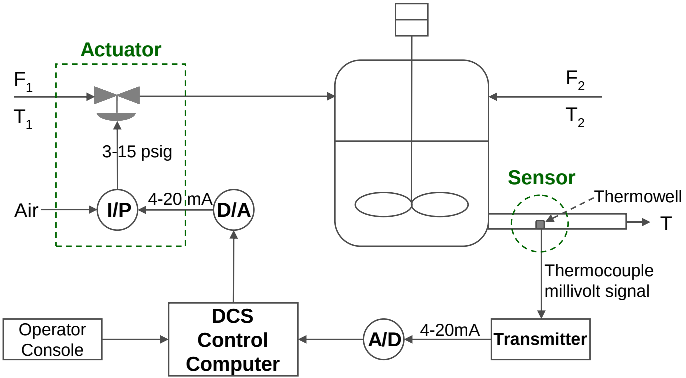
What do we need?

- Sensor (e.g., thermocouple)
- Transmitter (e.g., signal converter/amplifier/conditioner)
- Transmission Line (e.g., electrical line, air tube, data line)
- Controller (e.g., computer)
- Actuator (e.g., control valve)

Typical Setup



Exemplary Control Loop: Temperature Control



Implementation Modes

- Digital
  - Transmission: either analog signal (which gets converted to digital signal just before entering the controller) or digital signal (sequence of 0-1 binary pulses)
  - A/D: converts analog signal to digital signal
  - D/A: converts digital signal to analog signal
  - Controller: digital computer
  - High flexibility and easy reconfiguration
  - Easy access of remote data and past data

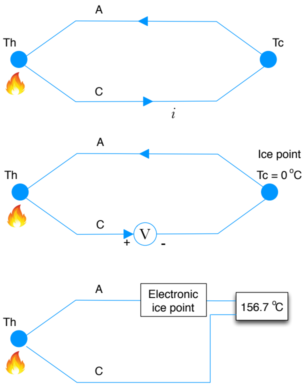
Sensors

- Physical properties ⇒ signals appropriate for electric and mechanical processing
- Common sensors
    - Temperature: thermocouple, resistance temperature detector (RTD)
    - Pressure: bellows, bourdon tube, diaphragm
    - Differential pressure: same as above
    - Flow rate: orifice, venturi, vane, magnetic flow meter
    - Liquid level: free float, fixed float, differential pressure
    - pH: pH meter (electrode)
    - Viscosity: differential pressure under constant flowrate
    - Chemical composition: gas chromatograhy

See Table 8.1 (p. 143) in the textbook.

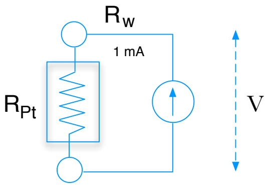
Thermocouple

- Two metal junctions at different temperatures generating a voltage that is proportional to the temperature.
    - Chromel-alumel (K-type): most popularly used
    - Iron-constantan (J-type): higher emf
    - Copper-constantan (T-type): cryogenic temperature
    - 13% Rh.Pt-Pt (R-type): high temperature (>900°C)



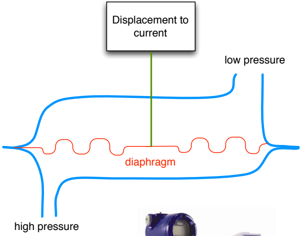
Resistance Thermometer Detector (RTD)

- Resistance of certain metals depends strongly upon their temperature
- Platinum and nickel are typical choices
- More accurate and repeatable but more expensive and less rugged than TCs
- Used for important temperature control points (reactors, distillation columns)



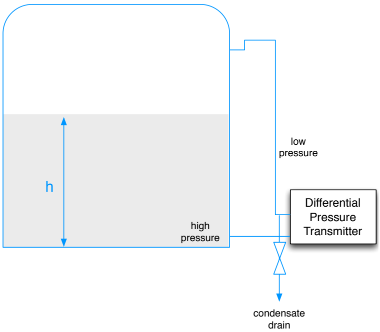
Pressure Measurement

DP Cells



- Strain guages
  - High pressure measurements
  - Stretched wire (elastic) $\rightarrow$ Increased resistance

Level Measurement: Closed Tank



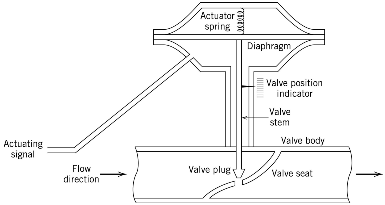
$$\Delta P = \rho g h$$

Transmitter

- Sensor signal (typically in mV) $\Rightarrow$ signal that can be transmitted and accepted by the controller (e.g., 4--20mA)
- Example
  - $50° C - 150° C \Rightarrow$ 4mA -- 20mA
  - Gain of the transmitter = 16mA/$100° C$ = 0.16 mA/$° C$
  - Zero of the transmitter = value when the output is at the minimum (4mA) = $50° C$
- Why make the minimum output 4mA instead of 0mA?

Actuators

- Convert controller output signal (4--20 mA or 3--15 psig) to physical adjustment in the process input variables (MVs).
- For process control, the most common type of actuator is the control valve.
- Others include
    - Variable speed pumps
    - Hydraulic actuators



Air-to-Open vs. Air-to-Close

- Air-to-Open (A-O) or Fail-Close (FC)
  - More air $\rightarrow$ larger opening $\Rightarrow$ No air $\rightarrow$ valve closes
- Air-to-Close (A-C) or Fail-Open (FO)
  - More air $\rightarrow$ smaller opening $\Rightarrow$ No air $\rightarrow$ valve opens completely
- Proper type to use is determined from safety considerations
  - Air-to-Close: Coolant valve in an exothermic reactor or in a condenser of a distillation column
  - Air-to-Open: Steam valve in a reactor, inlet flow valve to a tank
- Control Valve Dynamics

$$\frac{U(s)}{P(s)} = G_v(s) = \frac{K_v}{\tau_v s + 1}$$

Specifying and Sizing Control Valves

- Basic valve equation

$$q(\ell) = C_v f(\ell)\sqrt{\frac{\Delta P_v}{g_s}} \quad 0 \le \ell \le 1$$

  ℓ: valve lift, g_s: specific gravity of the fluid (water = 1)

- Valve size: determines C_v (valve coefficient)
- Valve trim type (valve characteristic)
  - Linear: $f(\ell) = \ell$
  - Square-root (Quick opening): $f(\ell) = \sqrt{\ell}$
  - Equal percentage: $f(\ell) = R^{\ell-1}$, $R \approx 20 - 50$