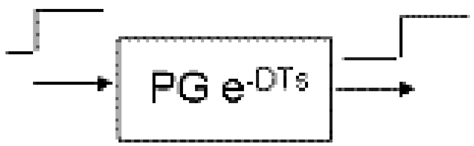
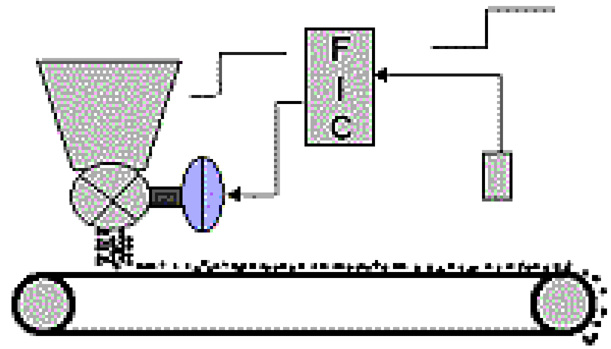
Lecture 11 - Processes with Deadtime, Internal Model Control

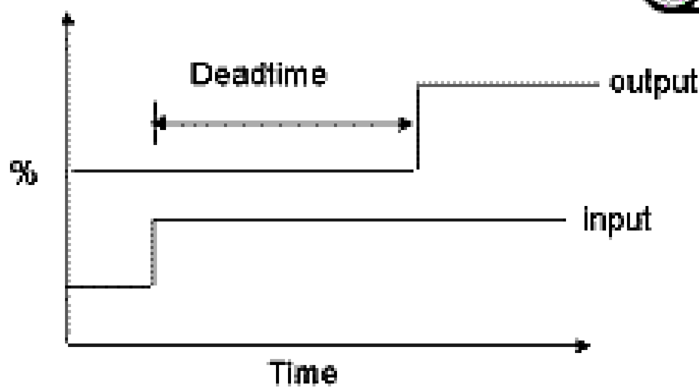
- Processes with deadtime
- Model-reference control
- Deadtime compensation: Dahlin controller
- IMC
- Youla parametrization of all stabilizing controllers
- Nonlinear IMC
  - Receding Horizon - MPC - Lecture 14

Processes with Deadtime

- Examples: transport deadtime in paper, mining, oil
- Deadtime = transportation time

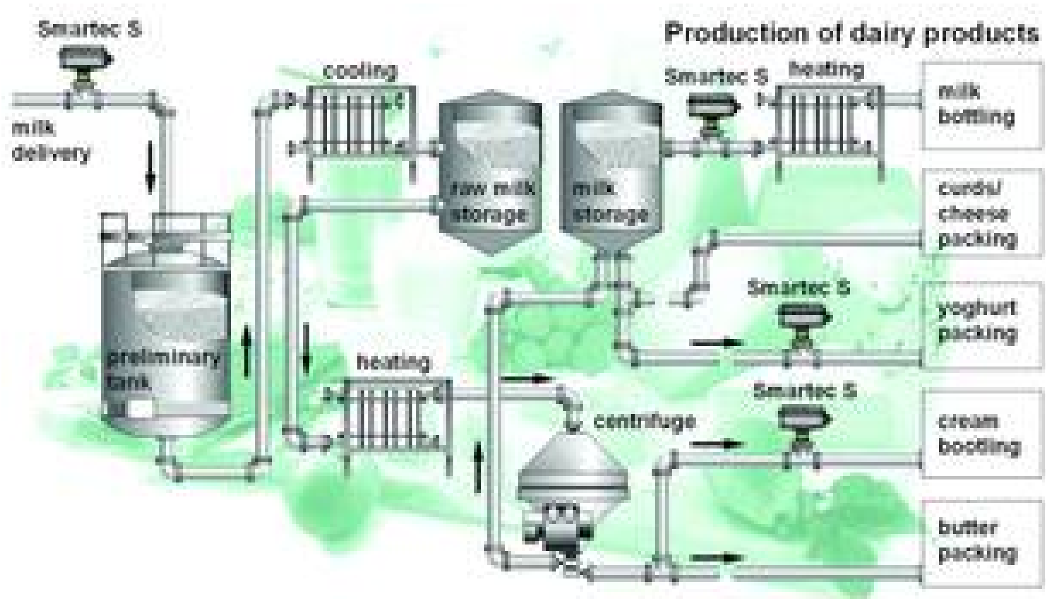


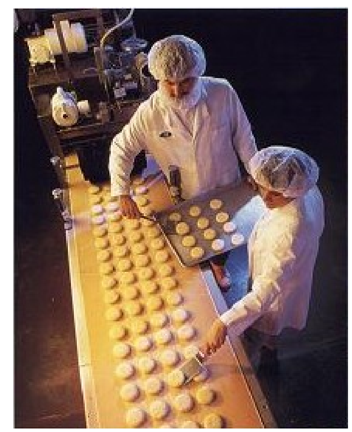




Processes with Deadtime

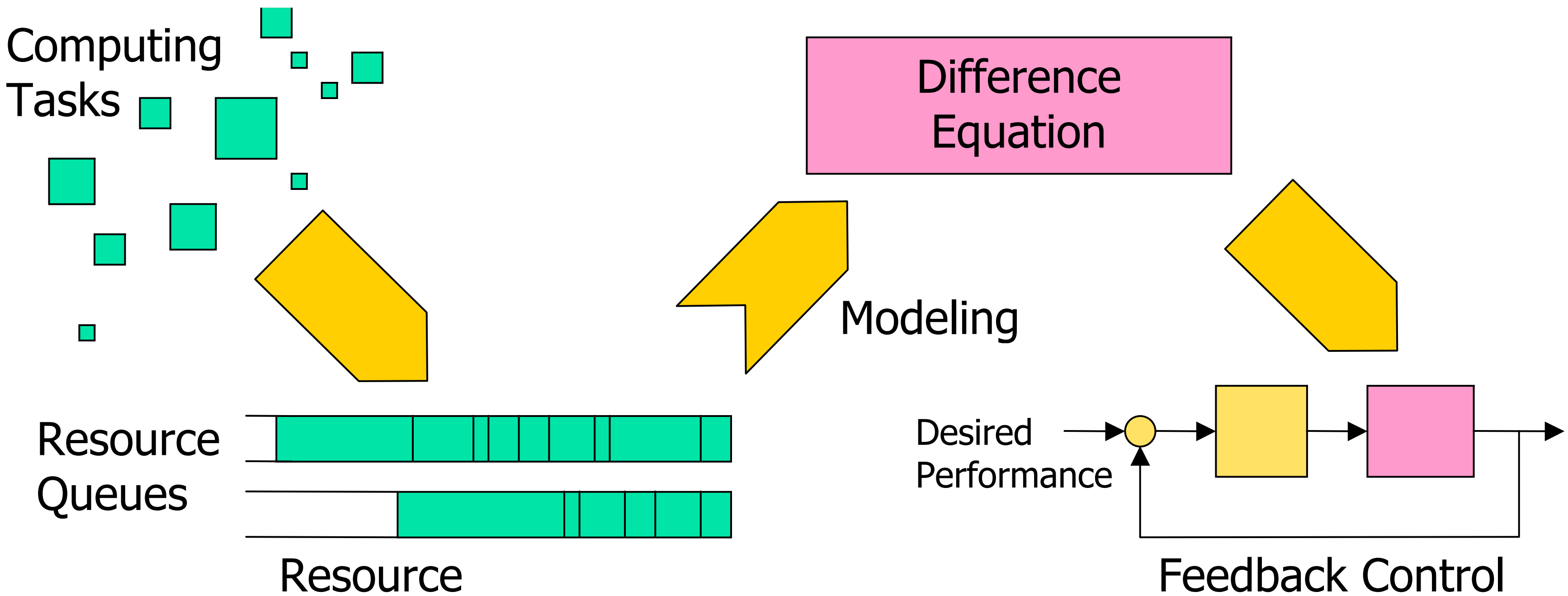
- Example: transport deadtime in food processing





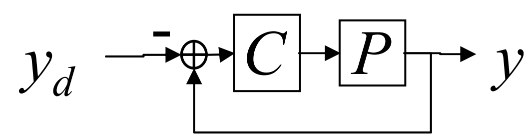
Processes with Deadtime

- Example: resource allocation in computing



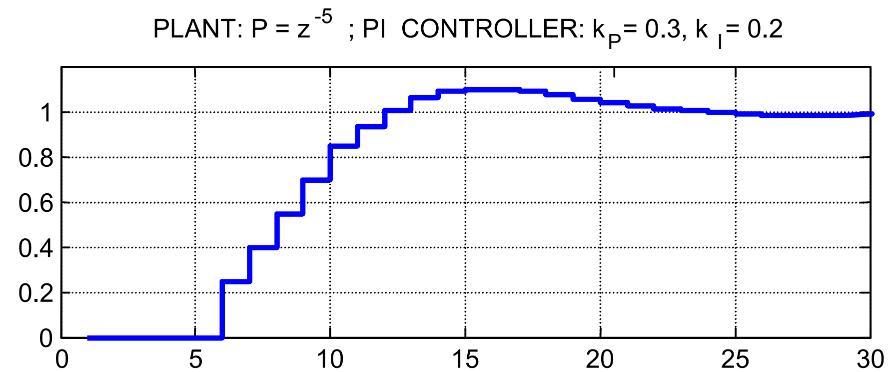
Control of process with deadtime

- PI control of a deadtime process

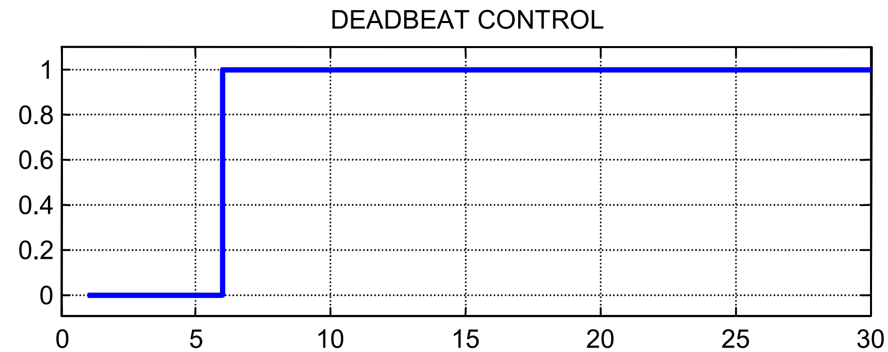


$$P = e^{-sT_D} \quad \text{continuous time}$$

$$P = z^{-d} \quad \text{discrete time}$$



- Can we do better?
  - Make $$\frac{PC}{1+PC} = z^{-d}$$
  - Deadbeat controller



$$PC = \frac{z^{-d}}{1 - z^{-d}} \Rightarrow C = \frac{1}{1 - z^{-d}}$$

$$u(t) = u(t-d) + e(t)$$

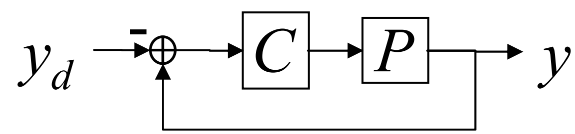
Model-reference Control

- Deadbeat control has bad robustness, especially w.r.t. deadtime
- More general model-reference control approach
  - make the closed-loop transfer function as desired

$$\frac{P(z)C(z)}{1+P(z)C(z)} = Q(z)$$

$$C(z) = \frac{1}{P(z)} \cdot \frac{Q(z)}{1-Q(z)}$$

$Q(z)$ is the reference model for the closed loop



- Works if $Q(z)$ includes a deadtime, at least as large as in $P(z)$. Then $C(z)$ comes out causal.

Causal Transfer Function

$$C(z) = \frac{B(z)}{A(z)} = \frac{b_0 z^M + b_1 z^{M-1} + ... + b_N}{z^N + a_1 z^{N-1} + ... + a_N}$$

$$= \frac{b_0 z^{M-N} + b_1 z^{M-N-1} + ... + b_N z^{-N}}{1 + a_1 z^{-1} + ... + a_N z^{-N}}$$

- Causal implementation requires that $N \geq M$

$$\underbrace{\left(1 + a_1 z^{-1} + ... + a_N z^{-N}\right)}_{A(z)} u(t) = \underbrace{\left(b_0 z^{M-N} + b_1 z^{M-N-1} + ... + b_N z^{-N}\right)}_{B(z)} e(t)$$

Dahlin's Controller

- Eric Dahlin worked for IBM in San Jose (?) then for Measurex in Cupertino.
- Dahlin's controller, 1967

$$C(z) = \frac{1}{P(z)} \cdot \frac{Q(z)}{1 - Q(z)}$$

$$P(z) = \frac{g(1-b)}{1-bz^{-1}} z^{-d}$$

• plant, generic first order response with deadtime

$$Q(z) = \frac{1-\alpha}{1-\alpha z^{-1}} z^{-d}$$

• reference model: 1st order+deadtime

$$C(z) = \frac{1-bz^{-1}}{g(1-b)} \cdot \frac{1-\alpha}{1-\alpha z^{-1} - (1-\alpha) z^{-d}}$$

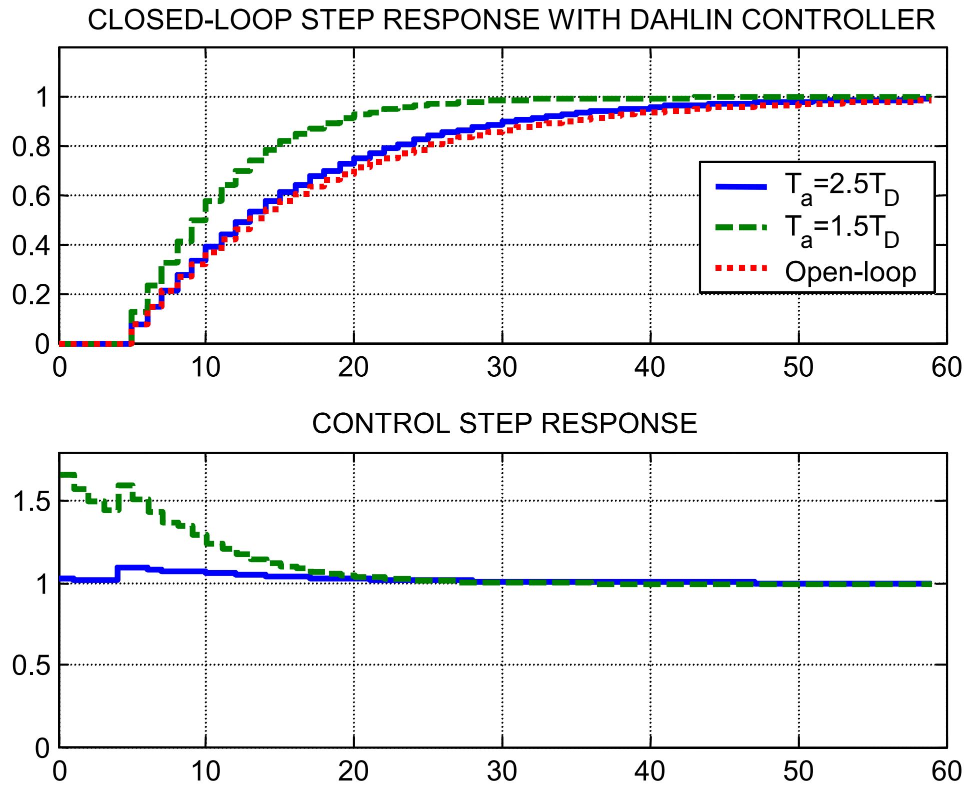
• Dahlin's controller

- Single tuning parameter: α - tuned controller

  a.k.a. λ - tuned controller

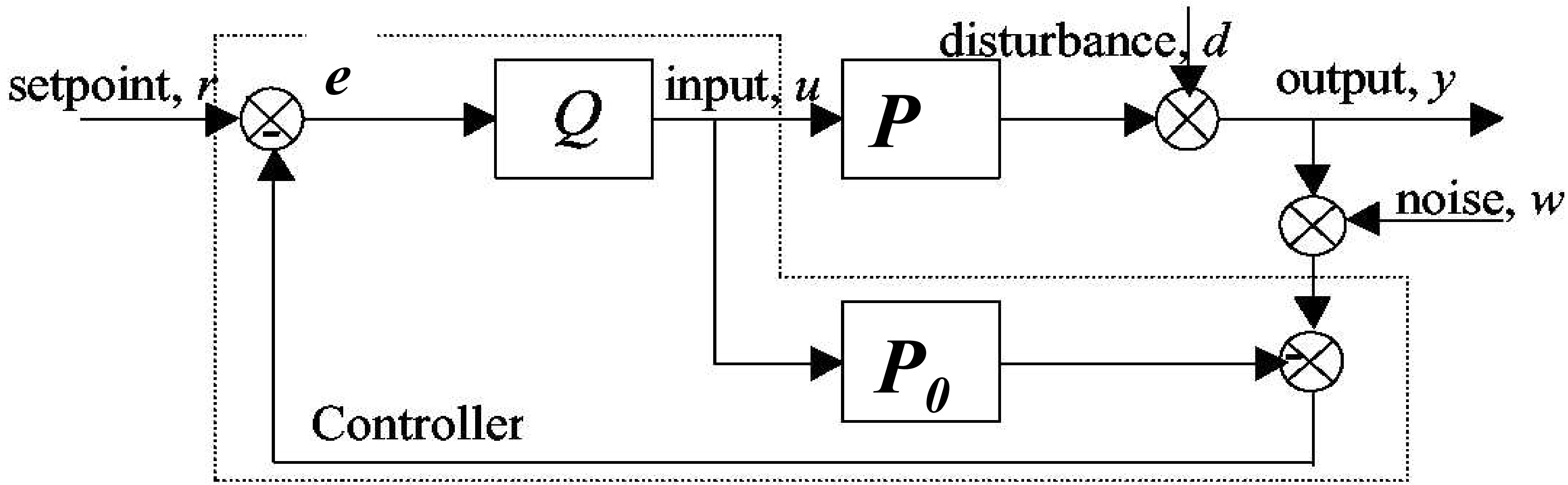
Dahlin's Controller

- Dahlin's controller is broadly used through paper industry in supervisory control loops - Honeywell-Measurex, 60%.
- Direct use of the identified model parameters.
- Industrial tuning guidelines: Closed loop time constant = 1.5-2.5 deadtime.



Internal Model Control - IMC

General controller design approach; some use in process industry



$$e = r - (y - P_0 u)$$

$$u = Qe$$

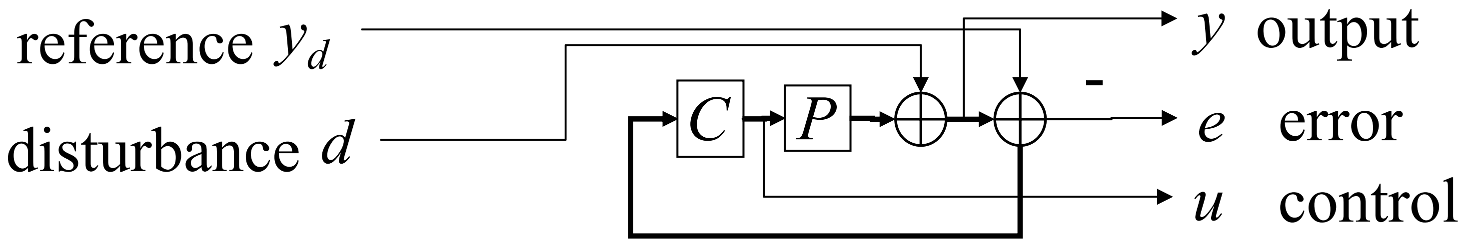
$$\Rightarrow \quad C = \frac{Q}{1 - QP_0}$$

- continuous time s
- discrete time z

Reference model: $T = QP_0$

Filter Q Internal model: P_0

IMC and Youla parametrization



$$C = \frac{Q}{1 - QP_0}$$

- Sensitivities

$$S = 1 - QP_0 \qquad d \to y$$

$$T = QP_0 \qquad y_d \to y$$

$$S_u = Q \qquad d \to u$$

$$Q = \frac{C}{1 + CP_0}$$

- If Q is stable, then S, T, and the loop are stable
- If the loop is stable, then Q is stable

- Choosing various stable Q parameterizes all stabilizing controllers. This is called Youla parameterization
- Youla parameterization is valid for unstable systems as well

Q-loopshaping

- Systematic controller design: select Q to achieve the controller design tradeoffs
- The approach used in modern advanced control design: H_2/H_∞, LMI, H_∞ loopshaping

- Q-based loopshaping: Loopshaping

$$S = 1 - QP_0 \qquad S << 1 \Rightarrow Q \approx (P_0)^{-1}$$ • in band

- Recall system inversion Inversion

Q-loopshaping

- Loopshaping

$$S = 1 - QP_0 \qquad S << 1 \Rightarrow Q \approx (P_0)^{-1} \qquad \bullet \text{ in band}$$

$$T = QP_0 \qquad T << 1 \Rightarrow QP_0 << 1 \qquad \bullet \text{ out of band}$$

- For a minimum phase plant

$$Q = P_0^{\dagger} = F(P_0)^{-1}, \qquad T = QP_0 = F$$

$$F = \frac{1}{(1+\lambda s)^n} \qquad S = 1 - QP_0 = 1 - F$$

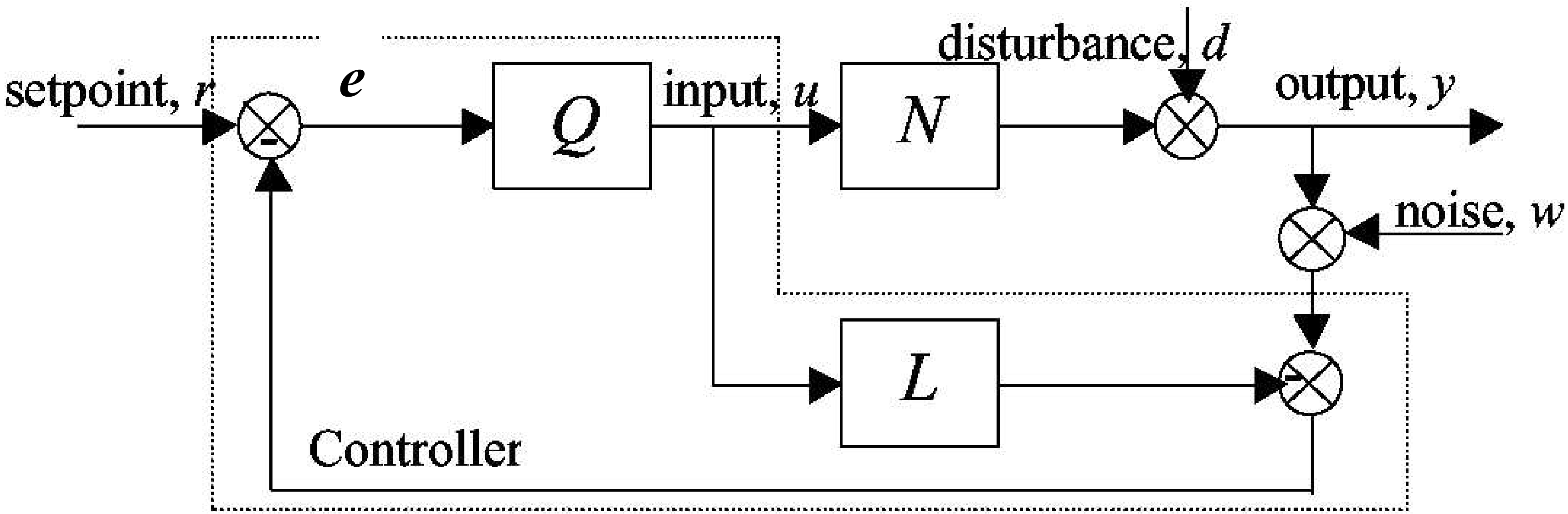
- F is called IMC filter, $F \approx T$, reference model for the output
- Lambda-tuned IMC

IMC extensions

- Multivariable processes
- Nonlinear process IMC
- Multivariable predictive control - Lecture 14

Nonlinear process IMC

- Can be used for nonlinear processes
  - linear *Q*
  - nonlinear model *N*
  - linearized model *L*



Industrial applications of IMC

- Multivariable processes with complex dynamics
- Demonstrated and implemented in process control by academics and research groups in very large corporations.
- Not used commonly in process control (except Dahlin controller)
  - detailed analytical models are difficult to obtain
  - field support and maintenance
    - process changes, need to change the model
    - actuators/sensors off
    - add-on equipment

Dynamic inversion in flight control

$$\dot{v} = F(x,v) + G(x,v)u$$

$$u = G^{-1}(\dot{v}^{des} - F)$$

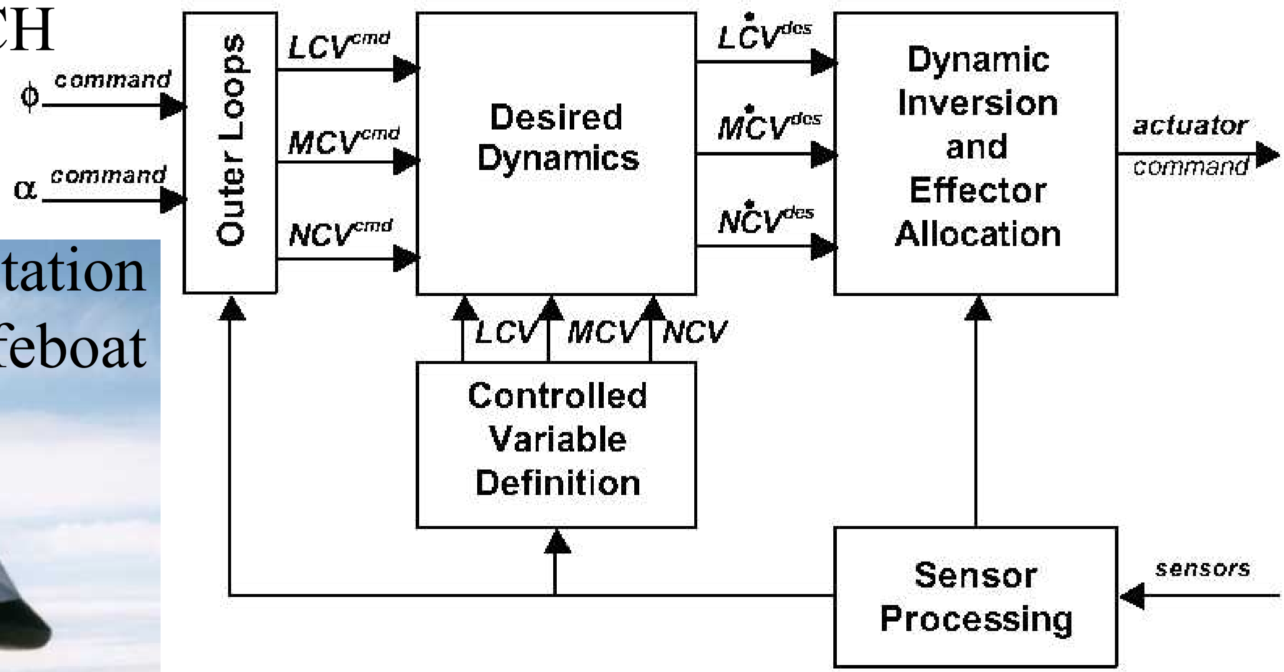
Reference model:

$$v = \frac{1}{s}\dot{v}^{des}$$

$$v = \begin{bmatrix} LCV \\ MCV \\ NCV \end{bmatrix}$$

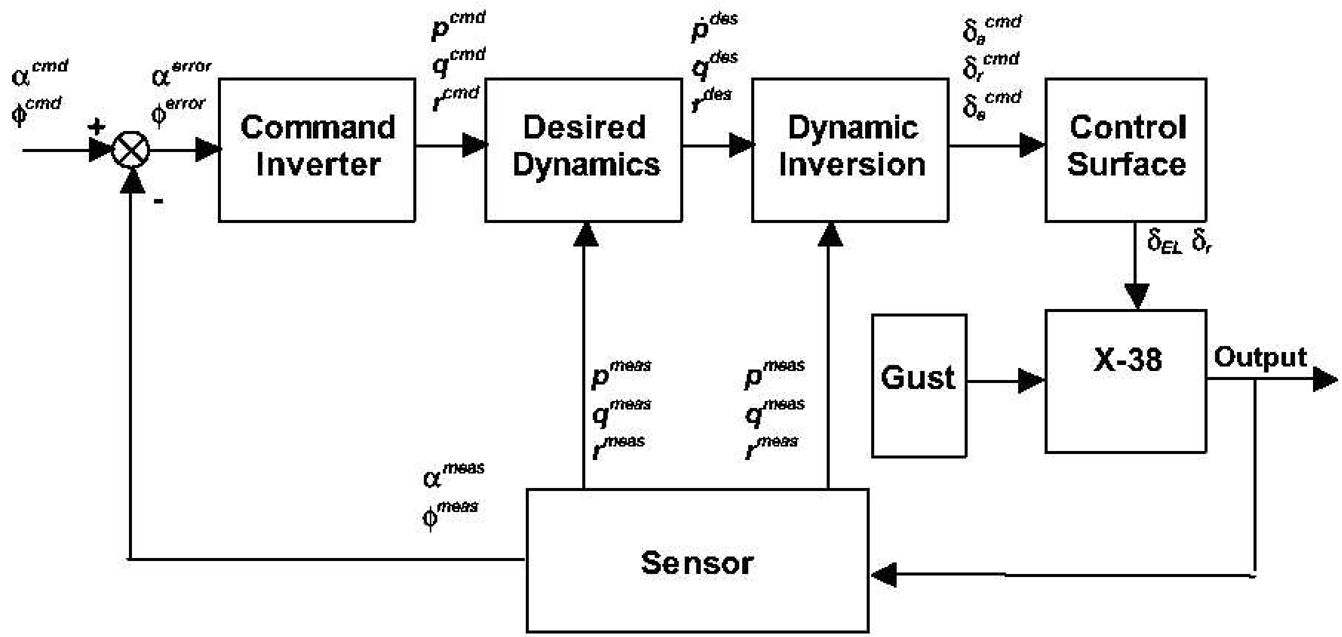
- Honeywell MACH
- Dale Enns

X-38 - Space Station Lifeboat



Dynamic inversion in flight control

- NASA JSC study for X-38
- Actuator allocation to get desired forces/moments
- Reference model (filter): vehicle handling and pilot ‘feel’
- Formal robust design/analysis (μ-analysis etc)



Summary

- Dahlin controller is used in practice
  - easy to understand and apply
- IMC is not really used much
  - maintenance and support issues
  - is used in form of MPC – Lecture 14
- Youla parameterization is used as a basis of modern advanced control design methods.
  - Industrial use is very limited.
- Dynamic inversion is used for high-performance control of air and space vehicles
  - this was presented for breadth, the basic concept is simple
  - need to know more of advanced control theory to apply in practice