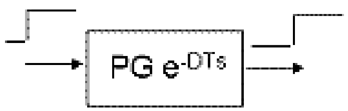
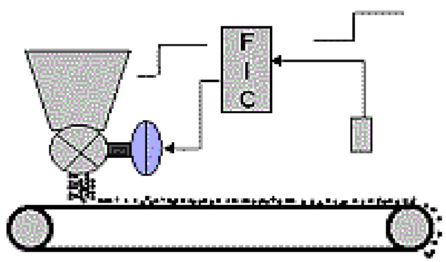
Lecture 9 - Processes with Deadtime, IMC

- Processes with deadtime
- Model-reference control
- Deadtime compensation: Dahlin controller
- IMC
- Youla parametrization of all stabilizing controllers
- Nonlinear IMC
  - Dynamic inversion - Lecture 13
  - Receding Horizon - MPC - Lecture 12

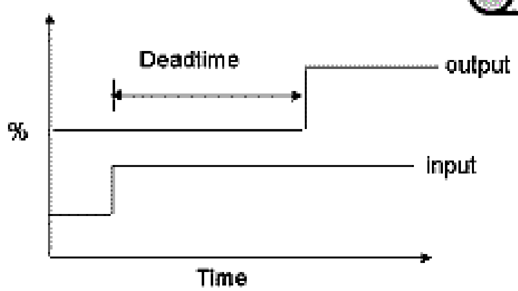
Processes with deadtime

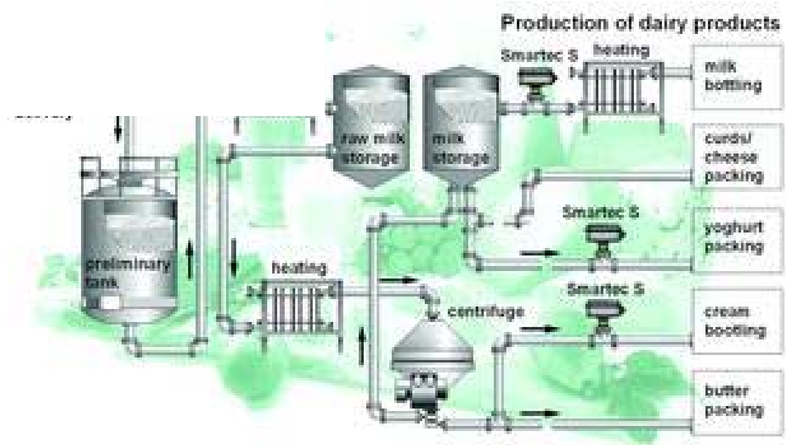
- Examples: transport deadtime in mining, paper, oil, food





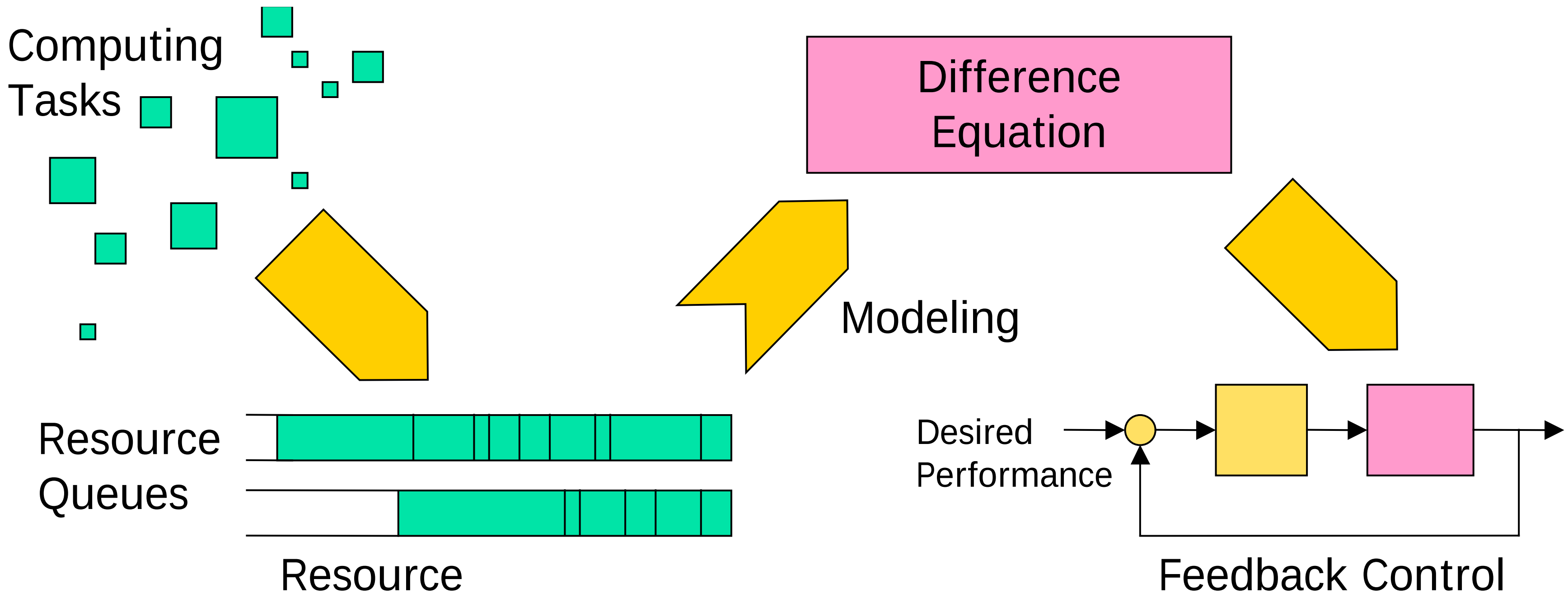
Deadtime = Transportation Time





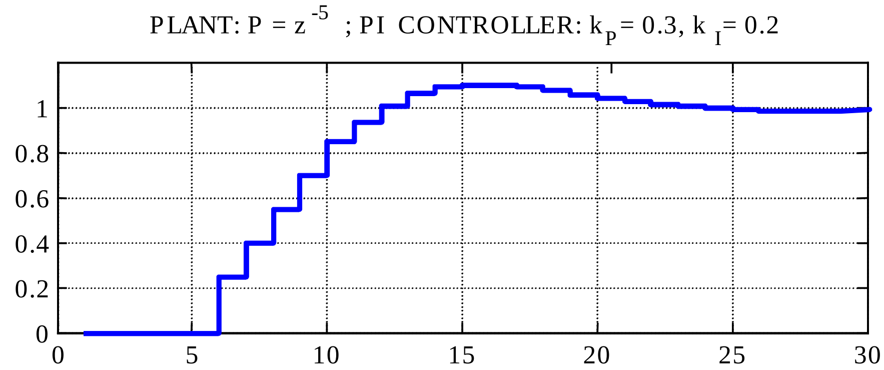
Processes with deadtime

- Example: resource allocation in computing



Control of process with deadtime

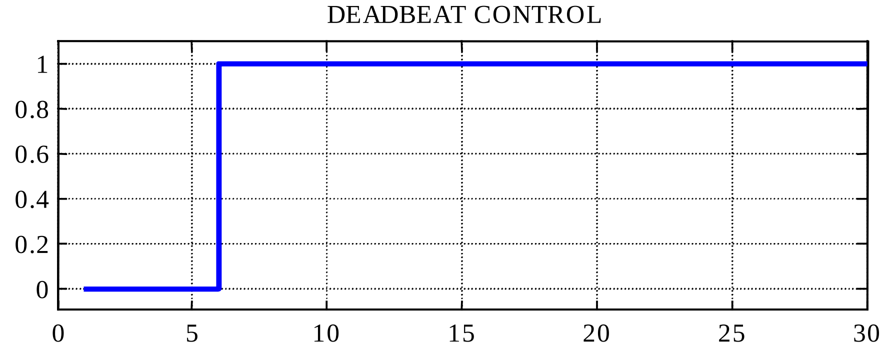
- PI control of a deadtime process



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

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

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

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

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

- Works if $Q(z)$ includes a deadtime, at least as large as in $P(z)$

Dahlin's controller

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

- Eric Dahlin worked for IBM in San Jose (?) then for Measurex in Cupertino.
- Dahlin's controller, 1968

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

• plant, generic first order response with deadtime

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

• reference model

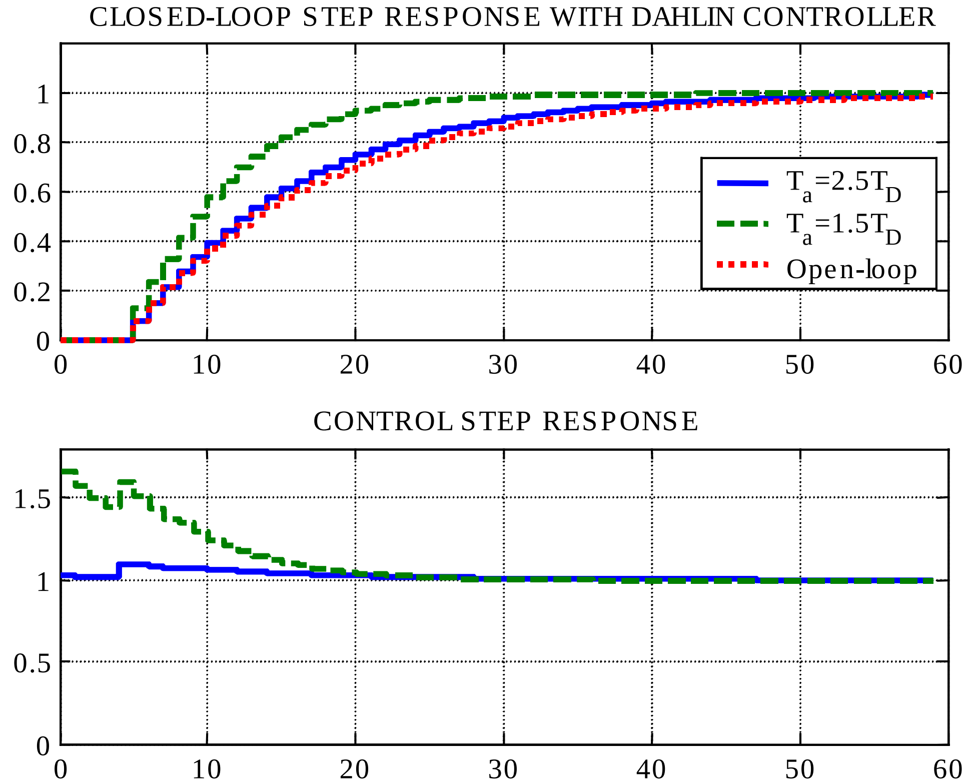
$$C(z) = \frac{1 - bz^{-1}}{g(1-b)} \cdot \frac{1-\alpha}{1 - \alpha z^{-1} - (1-\alpha) z^{-d}}$$

• Dahlin's controller

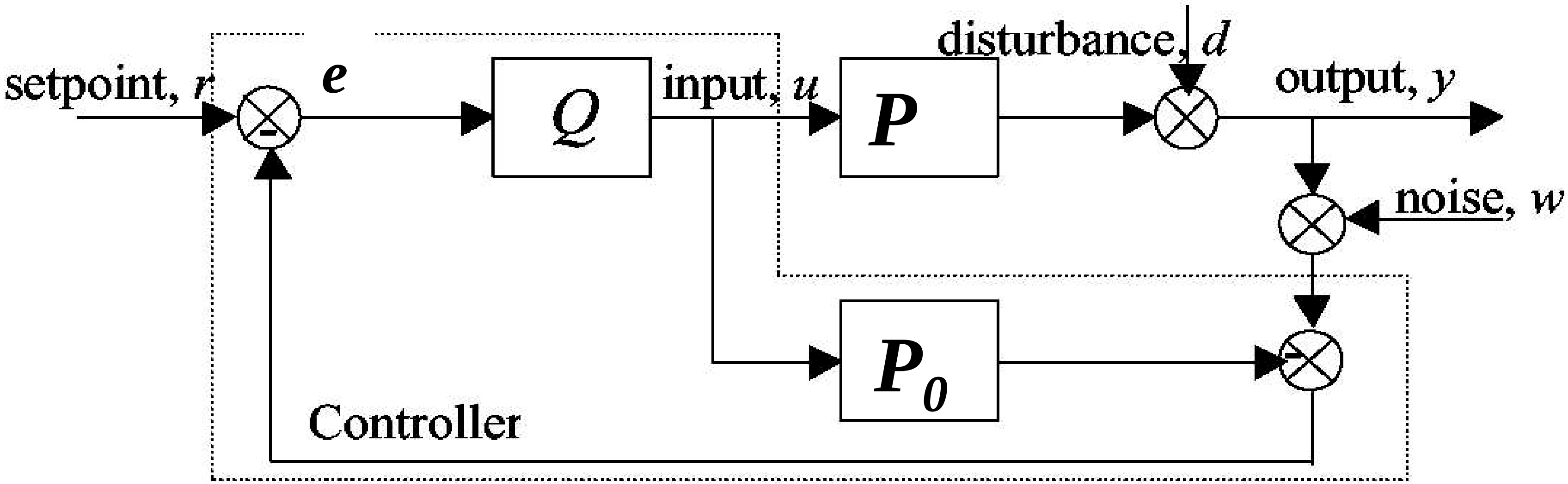
- Single tuning parameter: α - tuned controller

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



$$e = r - (y - Pu)$$
$$u = Qe$$

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

- continuous time *s*
- discrete time *z*

IMC and Youla parametrization

- Sensitivities

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

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

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

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

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

- If Q is stable, then S, T, and the loop are stable
- If 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 tradeoff
- The approach used in modern advanced control design: H_2/H_∞, LMI, H_∞ loopshaping

- Q-based loopshaping:

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

• in band

- Recall system inversion

Inversion

Q-loopshaping

- Loopshaping

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

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

- Lambda-tuned IMC †

$$Q = FP_0^{\dagger}, \qquad S = 1 - QP_0 \approx 1 - F$$

$$F = \frac{1}{\left(1 + \lambda s\right)^n}$$

Loopshaping

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

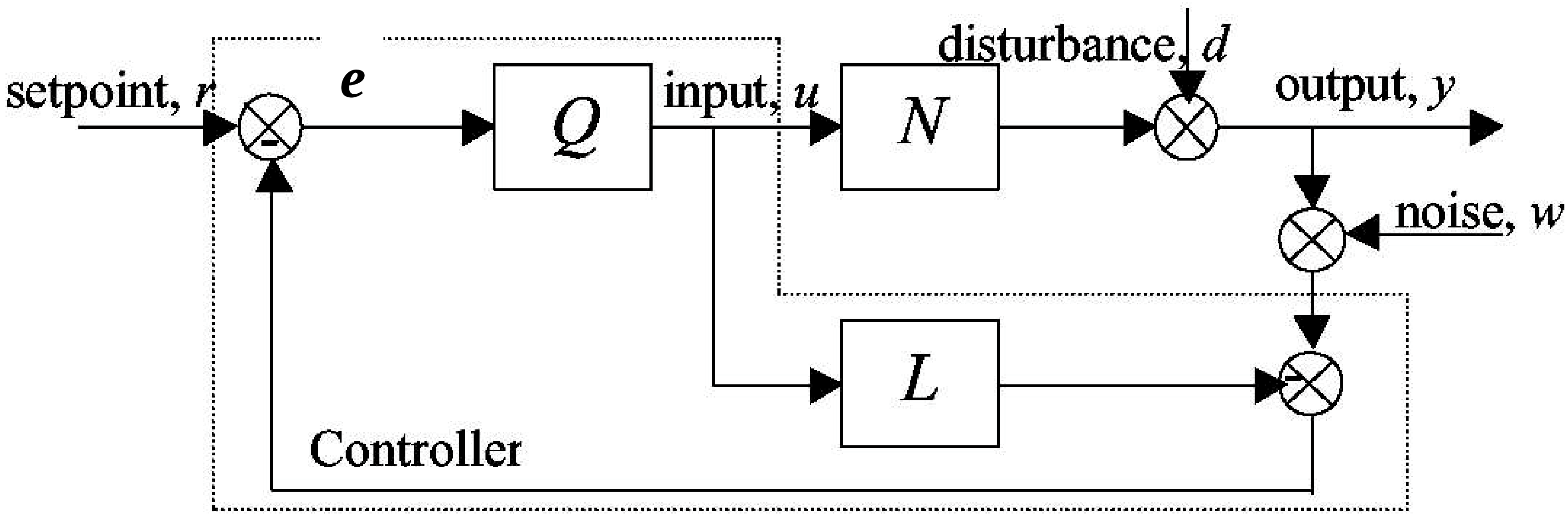
- For minimum phase plant $Q = FP_0^{\dagger} = F\left(P_0\right)^{-1}, \qquad T = F$

IMC extensions

- Multivariable processes
- Nonlinear process IMC
- Dynamic inversion in flight control - Lecture 13 - ?
- Multivariable predictive control - Lecture 12

Nonlinear process IMC

- Can be used for nonlinear processes
  - linear Q
  - nonlinear model P_0
  - 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

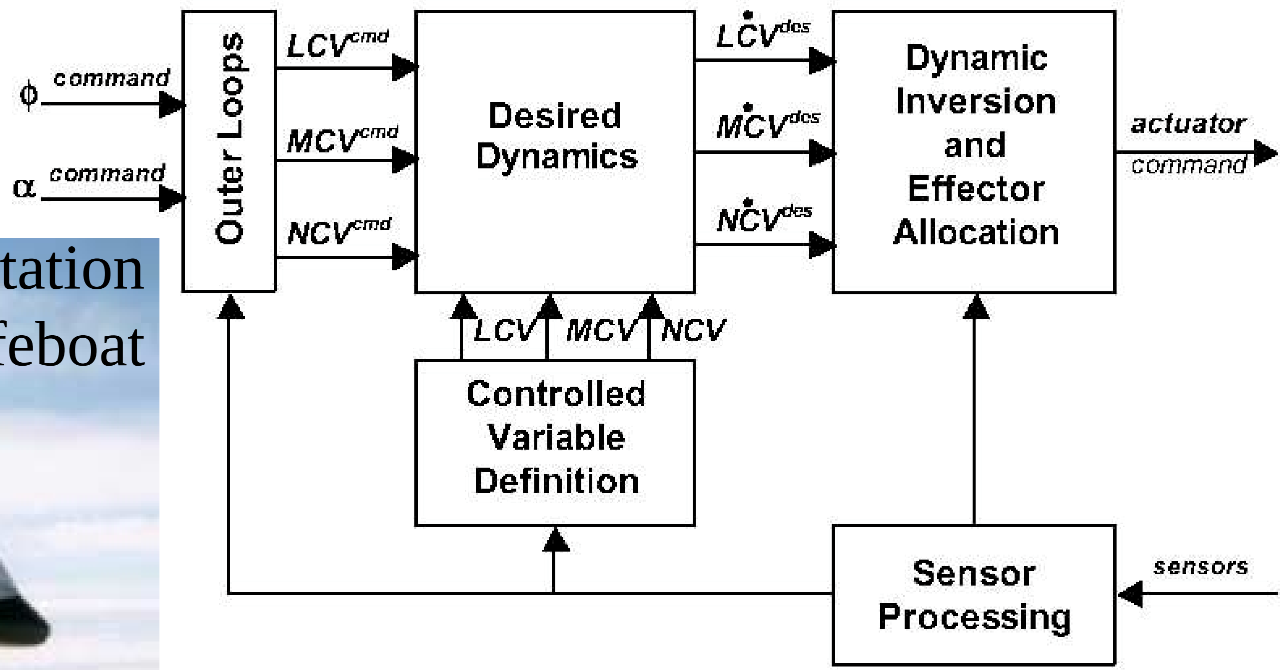
$$\dot{v} = F(x,v) + G(x,v)u$$

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

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

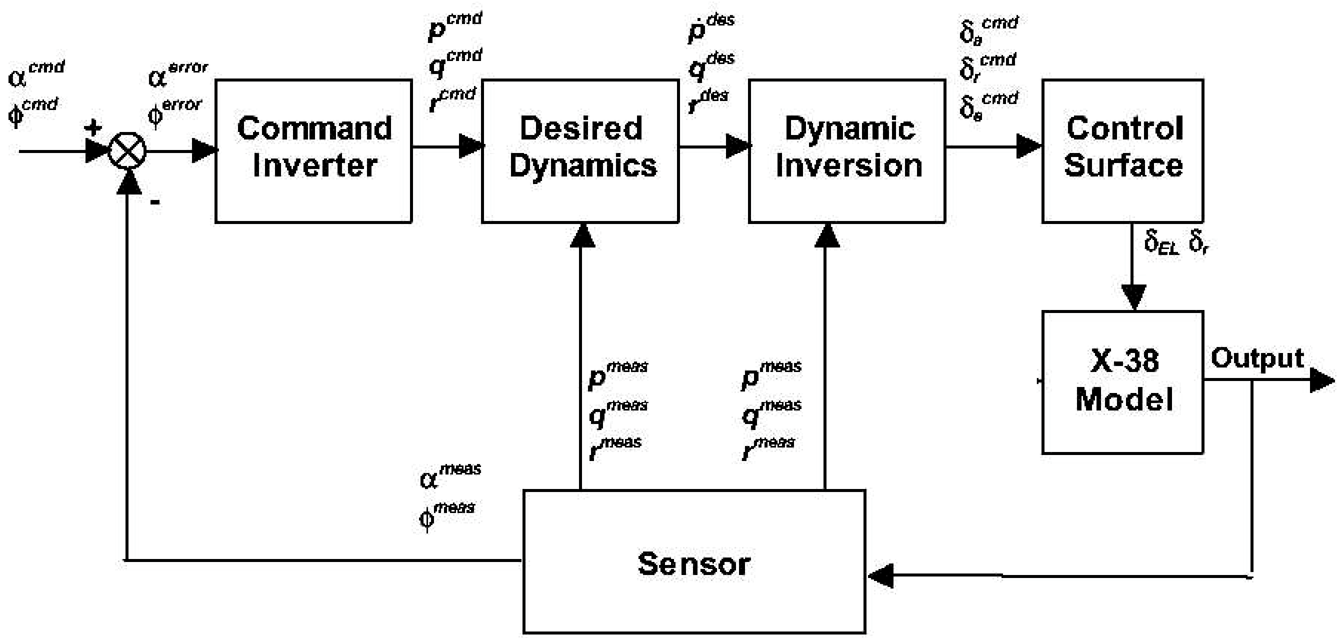
- Honeywell MACH


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
- 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