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

\[ P = e^{-sT_D} \] continuous time

\[ P = z^{-d} \] discrete time

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

\[ PC = \frac{z^{-d}}{1 - z^{-d}} \iff C = \frac{1}{1 - z^{-d}} \]

\[ u(t) = u(t - d) + e(t) \]
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 \( P(z) \). 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 \( N \geq M \)

\[ \left(1 + a_1 z^{-1} + ... + a_N z^{-N}\right)u(t) = \left(b_0 z^{M-N} + b_1 z^{M-N-1} + ... + b_N z^{-N}\right)e(t) \]
Dahlin’s Controller

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

\[
P(z) = \frac{g(1-b)}{1-bz^{-1}}z^{-d} \quad \text{• plant, generic first order response with deadtime}
\]

\[
Q(z) = \frac{1-\alpha}{1-\alpha z^{-1}}z^{-d} \quad \text{• reference model: } 1^{\text{st}} \text{ order+deadtime}
\]

\[
C(z) = \frac{1-bz^{-1}}{g(1-b)} \cdot \frac{1-\alpha}{1-\alpha z^{-1}-(1-\alpha)z^{-d}} \quad \text{• Dahlin’s controller}
\]

- Single tuning parameter: \( \alpha \) - tuned controller
  a.k.a. \( \lambda \) - tuned controller

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

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Gorinevsky
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

\[ e = r - (y - P_0 u) \]
\[ u = Qe \]

- continuous time \( s \)
- discrete time \( z \)

Reference model: \( T = QP_0 \)
Filter \( Q \)
Internal model: \( P_0 \)
IMC and Youla parametrization

- Sensitivities
  - $S = 1 - QP_0$ \(d \rightarrow y\)
  - $T = QP_0$ \(y_d \rightarrow y\)
  - $S_u = Q$ \(d \rightarrow u\)

- 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

\[ C = \frac{Q}{1 - QP_0} \]

\[ Q = \frac{C}{1 + CP_0} \]
$Q$-loopshaping

• Systematic controller design: select $Q$ to achieve the controller design tradeoffs

• The approach used in modern advanced control design: $H_2/H_\infty$, LMI, $H_\infty$ loopshaping

• $Q$-based loopshaping: $\text{Loopshaping}$

\[ S = 1 - QP_0 \quad S << 1 \Rightarrow Q \approx (P_0)^{-1} \quad \text{• in band} \]

• Recall system inversion $\text{Inversion}$
**$Q$-loopshaping**

- Loopshaping
  \[ S = 1 - QP_0 \quad S \ll 1 \Rightarrow Q \approx (P_0)^{-1} \quad \text{• in band} \]
  \[ T = QP_0 \quad T \ll 1 \Rightarrow QP_0 \ll 1 \quad \text{• out of band} \]

- For a minimum phase plant
  \[ Q = P_0^+ = F(P_0)^{-1}, \quad T = QP_0 = F \]
  \[ F = \frac{1}{(1 + \lambda s)^n} \]
  \[ S = 1 - QP_0 = 1 - F \]

- $F$ 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

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

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

- Honeywell MACH
- Dale Enns

Reference model:

\[ \nu = \frac{1}{s} \dot{v}^{des} \]

\[ \nu = \begin{bmatrix} LCV \\ MCV \\ NCV \end{bmatrix} \]
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