Controller structures

- Cascade control
- Mid-range control
- Ratio control
- Feedforward
- Delay compensation

Reading: *Systems Engineering and Process Control*: 10.1–10.6
Cascade control can be used for systems that can be split:

\[ u \rightarrow (G_{p2} \rightarrow y_2 \rightarrow G_{p1} \rightarrow y_1) \]

where

- both \( y_2 \) and \( y_1 \) can be measured
- \( G_{p2} \) is (or can be made) at least 10 times faster than \( G_{p1} \)

Example: \( G_{p1} = \frac{K_1}{1 + T_1s} \) and \( G_{p2} = \frac{K_2}{1 + T_2s} \) with \( T_2 < 0.1T_1 \)
Cascade control – block diagram

- Secondary controller $G_{c2}$ controls $y_2$
  - Inner loop is fast compared to outer loop
  - Often P-controller with high gain
  - For outer loop we have $y_2 \approx u_1$
- Primary controller $G_{c1}$ controls $y_1$
  - Often PI or PID controller
Example: Heat exchanger

Control may work poorly if, e.g.,:

- valve in nonlinear
- steam pressure varies (load disturbance)
Example: Heat exchanger with cascade control

- The inner loop controls the steam flow
- Setpoint to flow controller given by temperature controller
Example: Heat exchanger – simulation

With cascade control (solid) and without (dashed); disturbance at $t = 5$:
Mid ranging

Useful for processes with two inputs and one measurement, e.g.:

\[ \sum \]

- \( u_1 \) high precision but little working range
- \( u_2 \) low precision but big working range
Flow control with two controlled valves:

- Valve $v_1$ is small and has high accuracy
  - big risk of saturation
- Valve $v_2$ is big but has worse accuracy
- How can they cooperate?
Mid ranging – Example

Mid ranging:

- Fast controller $G_{R1}$ controls flow with little valve $v_1$
- Slow controller $G_{R2}$ adjusts big valve $v_2$ such that $v_1$ is in the middle of its working range
Mid ranging – simulation

Big valve (dashed) keeps little valve (solid) at 50%
- $G_{c1}$ and $G_{p1}$ forms a fast and accurate loop
- Input from $G_{c1}$ is measurement for $G_{c2}$
  - $r_{u1}$ chosen to middle of $u_1$'s working range
- $G_{c2}$ has low gain, maybe only I part
  - Rule of thumb: at least 10 times bigger time constant than fast loop
Ratio control

Example: Keep constant air/fuel ratio

Suppose we want $y_l/y_b = a$. Naive solution (control ratio $a$ directly):

Nonlinear, gain in second loop varies with $y_b$
Better solution:

- Setpoint for flow to first loop that is assumed slow
- Second loop is made fast and maintains desired ratio
Feedforward – Example

Concentration control

- Feedforward can compensate for sudden changes in acid concentration
Feedforward – Simulation of example

With feedforward (solid) and without (dashed); disturbance at $t = 5$: 

![Concentration and Valve position graphs](image-url)
How to choose compensator $G_{ff}(s)$? Depends on where disturbance $l$ enters the system.
Control of lower tank
Feedforward – Tank example

Feedforward from $l_1$:

Choose $G_{ff}(s) = -1$ to eliminate effect of disturbance
Feedforward from $l_2$:

Choose $G_{ff}(s) = -\frac{1}{G_{P1}}$ to eliminate effect of disturbance
Implementation of feedforward

The inverse $\frac{1}{G_{p1}(s)}$ can be problematic to implement.

**Example:**

$$G_{p1}(s) = \frac{1}{1 + sT} e^{-sL}$$

$$\frac{1}{G_{p1}(s)} = (1 + sT)e^{sL} \quad \text{(derivation and neg. time delay)}$$

**Common solutions:**

- Introduce lowpass filter (compare D part in PID-controller)
- Approximate negative time delays with 0
- Implement the static gain only
Dead time compensation

Example of dead time process:

\[ G_p(s) = \frac{K_p}{1 + sT} e^{-sL} \]

Hard to control if \( L > T \) (dead time dominated)

Frequency analysis:

\[ G_p(s) = G_{p0}(s)e^{-sL} \]
\[ |G_p(i\omega_c)| = |G_{p0}(i\omega_c)| \]
\[ \arg G_p(i\omega_c) = \arg G_{p0}(i\omega_c) - \omega_c L \]

The larger \( L \), the smaller the phase margin
Example: Control of paper machine

\[ G_p(s) = \frac{2}{1 + 2s} e^{-4s} \]

Simulation with cautious PI controller \((K = 0.2, T_i = 2.6)\); disturbance at \(t = 25\):
Example: Control of paper machine

Simulation with more aggressive PI controller ($K = 1, T_i = 1$):
Controller designed after model without delay. Model must be:

- asymptotically stable
- accurate enough
Analysis of Smith predictor

\[ G_p = G_{p0}e^{-sL} \] – real process

\[ \hat{G}_p = \hat{G}_{p0}e^{-s\hat{L}} \] – model of process

\[ \hat{G}_{p0} \] – model of process without dead time

\[ G_c \] – controller designed for \( \hat{G}_{p0} \)
Analysis of Smith predictor

Control signal:

\[ U = \frac{G_c}{1 - G_c(\hat{G}_p - \hat{G}_{p0})} E \]

Closed loop system:

\[ Y = \frac{G_p G_c}{1 - G_c(\hat{G}_p - \hat{G}_{p0}) + G_p G_c} R \]

Suppose \( G_p = \hat{G}_p \) (perfect model):

\[ Y = \frac{G_p 0 e^{-sL} G_c}{1 - G_c(G_p 0 e^{-sL} - G_p 0) + G_p 0 e^{-sL} G_c} R \]

\[ = \frac{G_p 0 G_c}{1 + G_p 0 G_c} e^{-sL} R \]

Like control of process without delay, but with delayed response
Example: Control of paper machine

Model without delay: \( G_{p0}(s) = \frac{2}{1 + 2s} \)

Simulation with aggressive PI controller \((K = 1, T_i = 1)\) and Smith predictor with perfect process model:
Example: Control of paper machine

Simulation with aggressive PI controller and Smith predictor with not perfect process model ($\hat{L} = 0.9L, \hat{T} = 0.9T$):

![Diagram showing control system response with aggressive PI controller and Smith predictor with imperfect model](image-url)
The Smith predictor – conclusions

- Works only for asymptotically stable systems
- Works only if process model is accurate
- Controller should be designed such that closed-loop time constant larger than process dead time

(Better variations for dead time compensation exist, but all rely on prediction using a process model)