Systems Engineering/Process Control L10

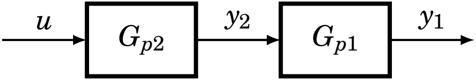
Controller structures

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

Reading: *Systems Engineering and Process Control*: 10.1–10.6

Cascade control

Cascade control can be used for systems that can be split:

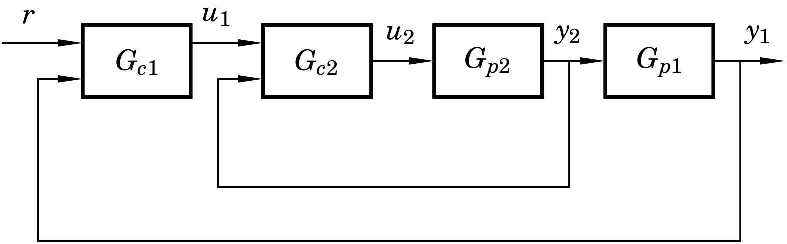


where

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

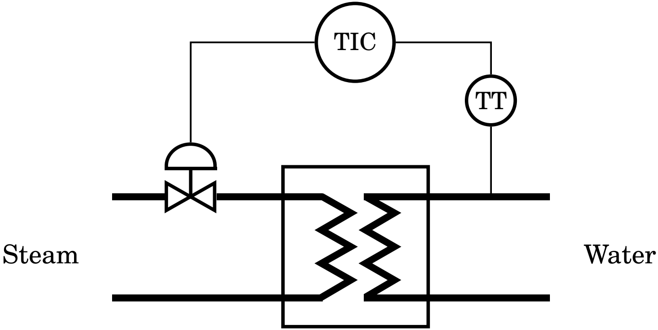
Example: $G_{p1} = \dfrac{K_1}{1 + T_1 s}$ and $G_{p2} = \dfrac{K_2}{1 + T_2 s}$ with $T_2 < 0.1 T_1$

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

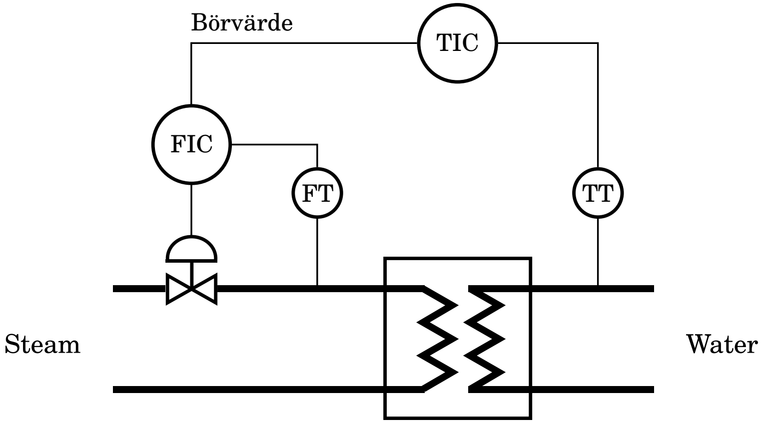
Example: Heat exchanger



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

- valve in nonlinear
- steam pressure varies (load disturbance)

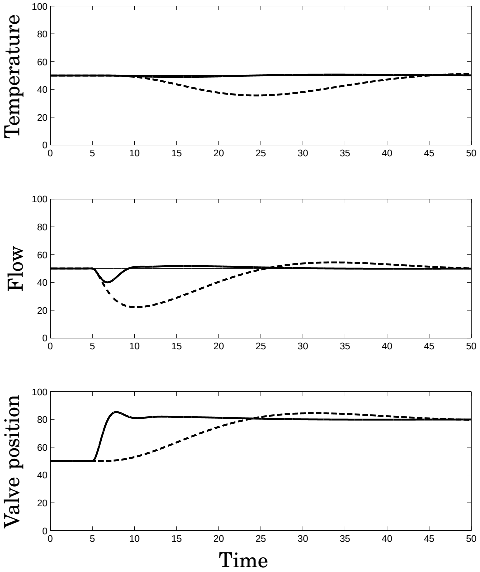
Example: Heat exchanger with cascade control



- The inner loop controls the steam flow
- Setpoint to flow controller given by temperature controller

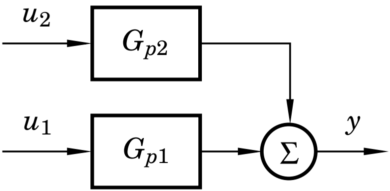
Example: Heat exchanger – simulation

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



Mid ranging

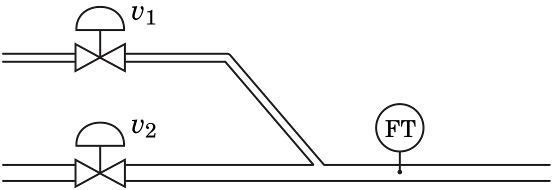
Useful for processes with two inputs and one measurement, e.g.,:



- u_1 high precision but little working range
- u_2 low precision but big working range

Mid ranging – Example

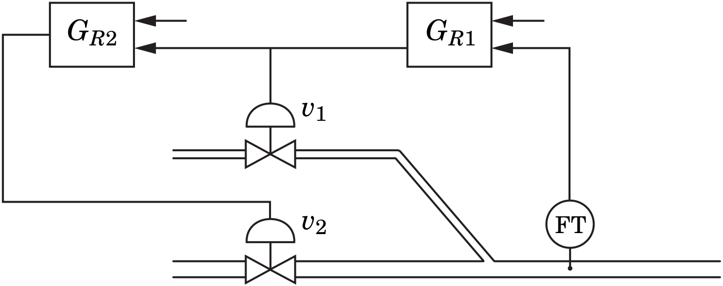
Flow control with two controlled valves:



- 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

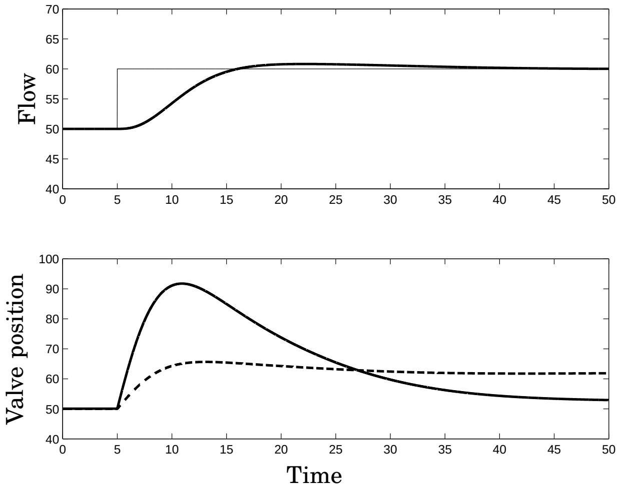
Mid ranging:



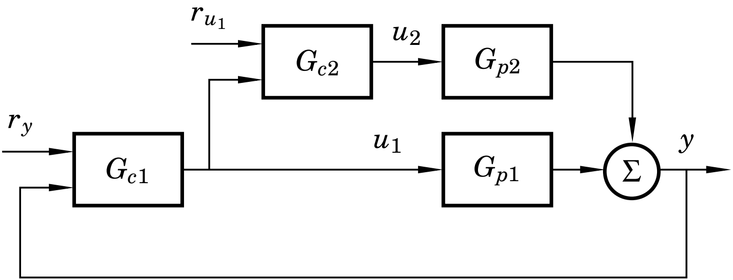
- Fast controller G_{R1} controls flow with little valve v_1
- Slow controller G_{R2} adjusts big valve v_2 such that v_1 is in the middle of its working range

Mid ranging – simulation

Big valve (dashed) keeps little valve (solid) at 50%



Mid ranging – Block diagram

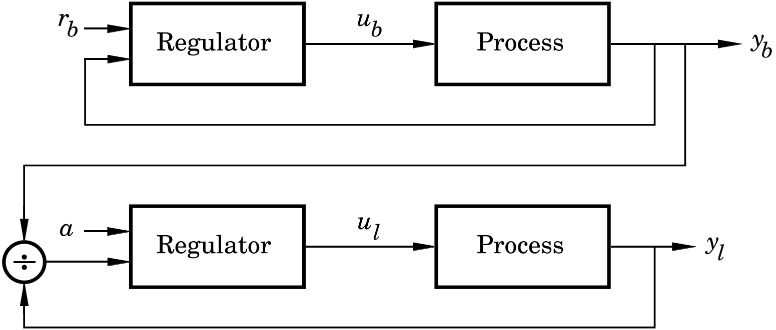


- G_{c1} and G_{p1} forms a fast and accurate loop
- Input from G_{c1} is measurement for G_{c2}
  - r_{u_1} chosen to middle of u_1:s working range
- G_{c2} has low gain, maybe only I part
  - Rule of thumb: at least 10 times bigger time constant than fast loop

Ratio control

Example: Keep constant air/fuel ratio

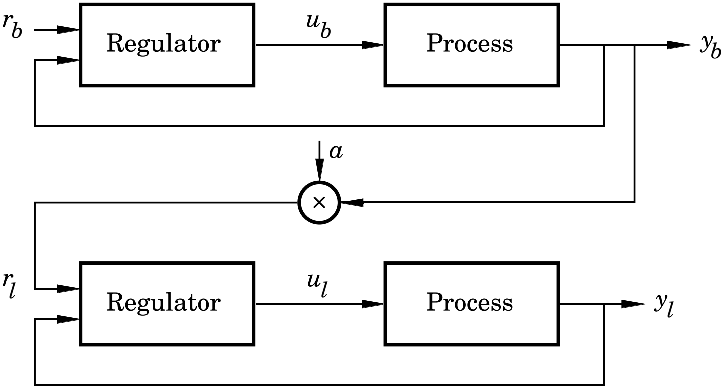
Suppose we want $y_l/y_b = a$. Naive solution (control ratio a directly):



Nonlinear, gain in second loop varies with y_b

Ratio control

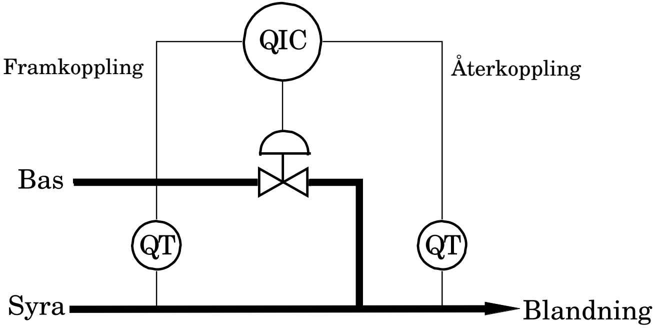
Better solution:



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

Feedforward – Example

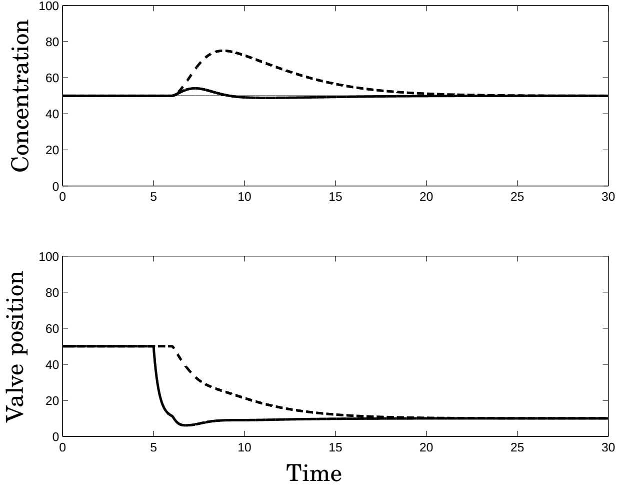
Concentration control



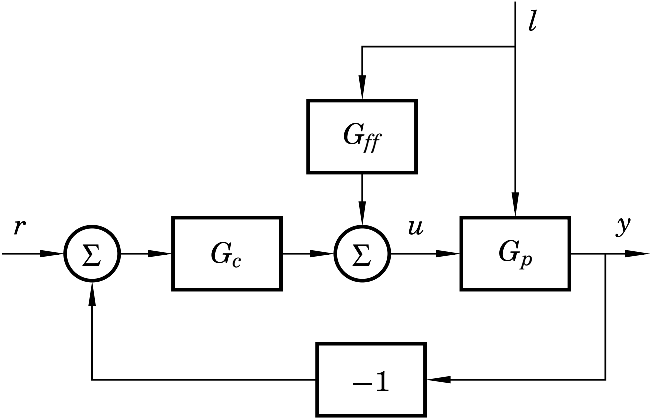
- Feedforward can compensate for sudden changes in acid concentration

Feedforward – Simulation of example

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



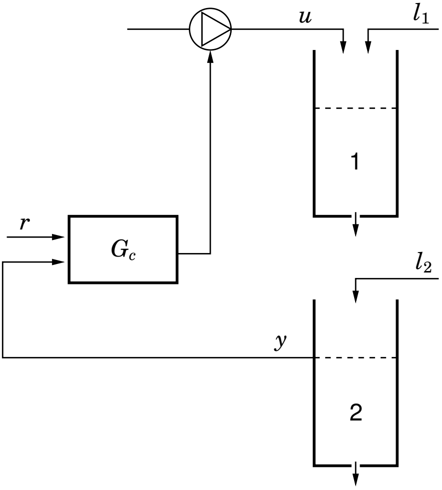
Feedforward – Block diagram



How to choose compensator $G_{ff}(s)$? Depends on where disturbance l enters the system.

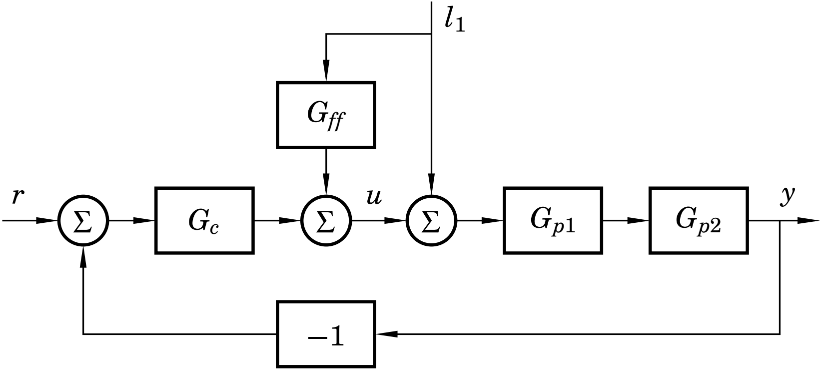
Feedforward – Tank example

Control of lower tank



Feedforward – Tank example

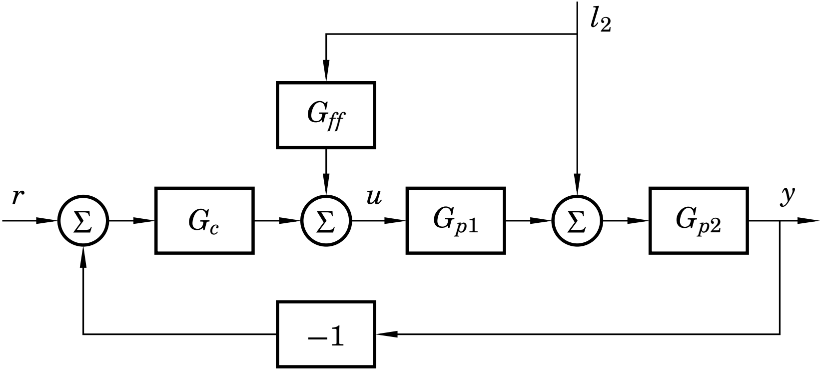
Feedforward from l_1:



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

Feedforward – Tank example

Feedforward from l_2:



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

Implementation of feedforward

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

Example:

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

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:

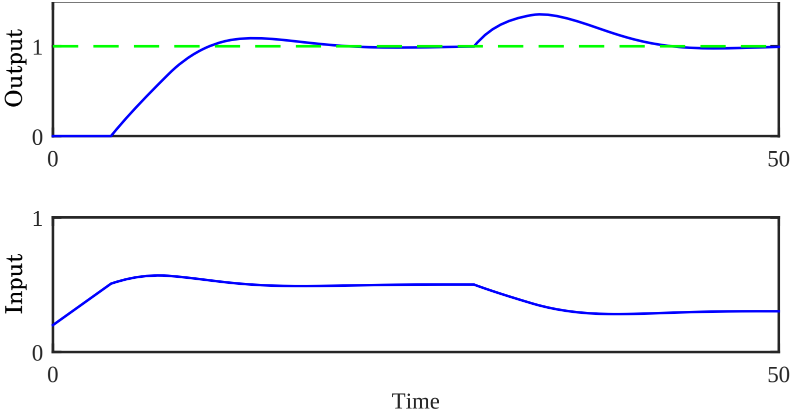
$$\begin{aligned} G_p(s) &= G_{p0}(s) e^{-sL} \\ |G_p(i\omega_c)| &= |G_{p0}(i\omega_c)| \\ \arg G_p(i\omega_c) &= \arg G_{p0}(i\omega_c) - \omega_c L \end{aligned}$$

The larger L, the smaller the phase margin

Example: Control of paper machine

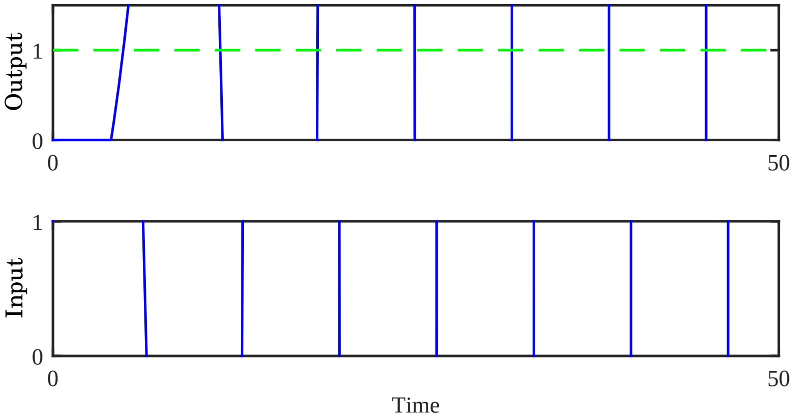
$$G_p(s) = \frac{2}{1+2s}e^{-4s}$$

Simulation with cautious PI controller ($K = 0.2$, $T_i = 2.6$); disturbance at $t = 25$:

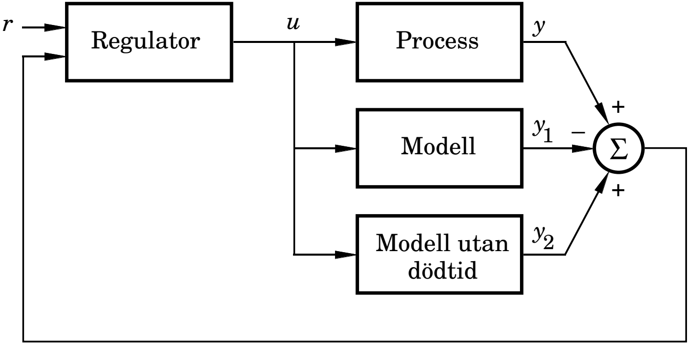


Example: Control of paper machine

Simulation with more aggressive PI controller ($K = 1$, $T_i = 1$):



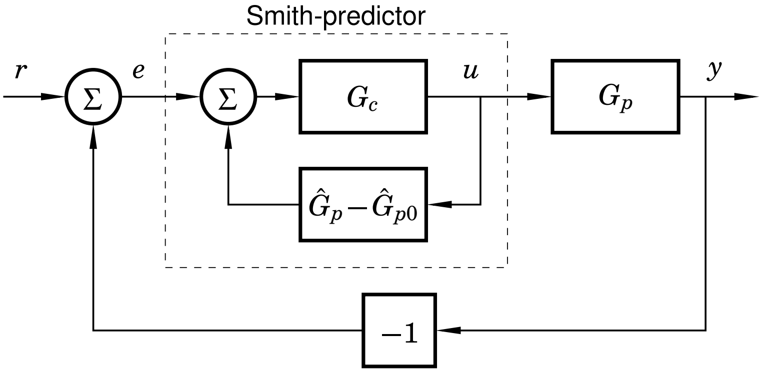
Dead time compensation with Smith predictor



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):

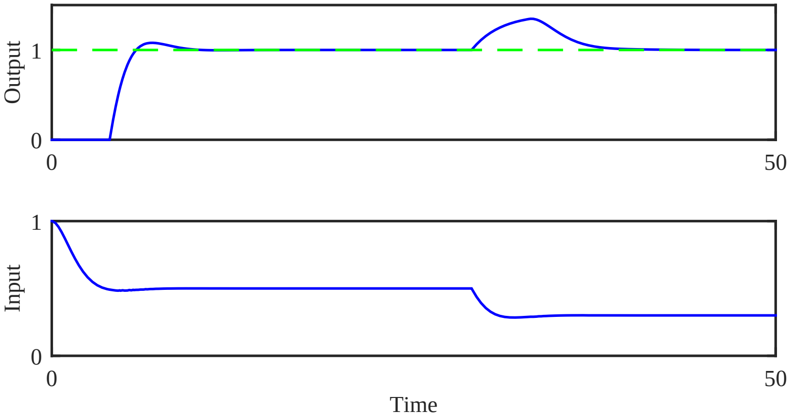
$$\begin{aligned} Y &= \frac{G_{p0} e^{-sL} G_c}{1 - G_c(G_{p0} e^{-sL} - G_{p0}) + G_{p0} e^{-sL} G_c} R \\ &= \frac{G_{p0} G_c}{1 + G_{p0} G_c} e^{-sL} R \end{aligned}$$

Like control of process without delay, but with delayed response

Example: Control of paper machine

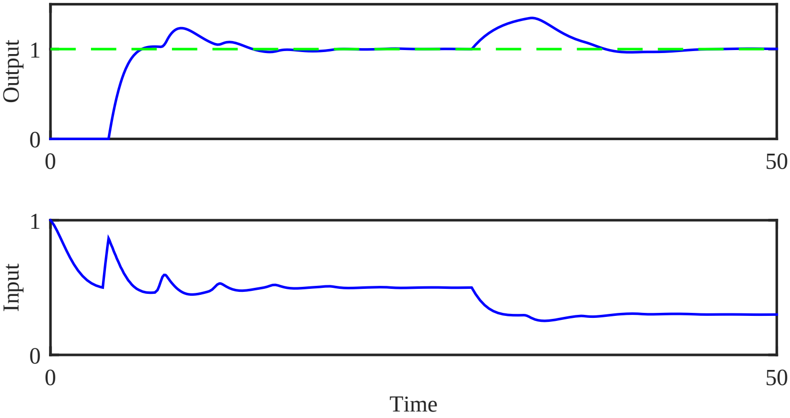
Model without delay: $G_{p0}(s) = \dfrac{2}{1+2s}$

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 ($\hat{L} = 0.9L$, $\hat{T} = 0.9T$):



The Smith predictor – conclussions

- 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)