Control concepts Dynamic Systems

Goals

As a student you should be able to:

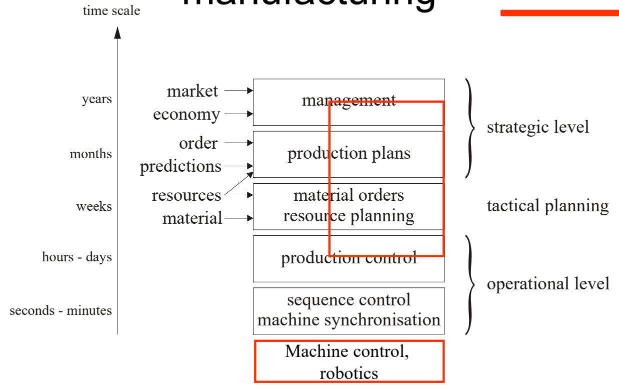
- Explain the basic concepts of control
- Understand different control structures and how they can be used to solve a control problem
- Understand practical limitations and know how to account for them

Control of continuous systems

Examples

- In process industry
  - Reactions, pressure, flow rates
- In vehicle control
  - Aircrafts, space, missiles, cars
- In manufacturing
  - Robotics, machine control

Continuous in discrete manufacturing



Components of control

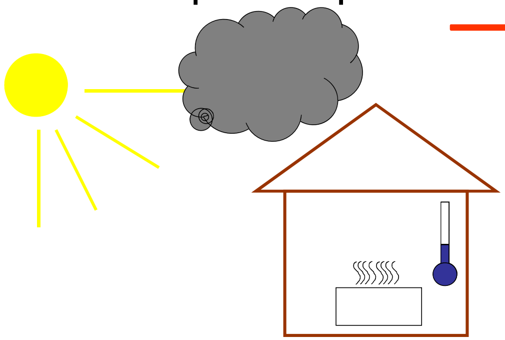
- Process / machine incl. controlled variable/state
- Sensor
- Controller
- Actuator
- Communication
- Data handling (SCADA) and storage (data bases)

Important controller concepts

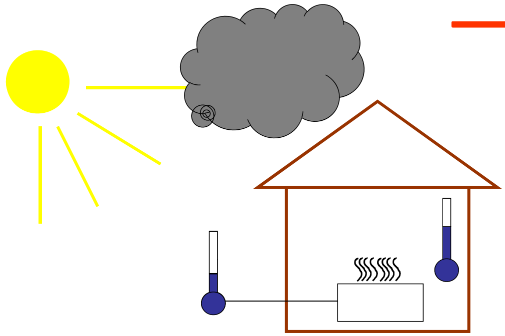
- Open loop
- Closed loop
- Feed-forward
- Feedback
- Stationary error
- Stability
- Time delays

Fundamental concepts of control that a control or automation engineer must know!!!

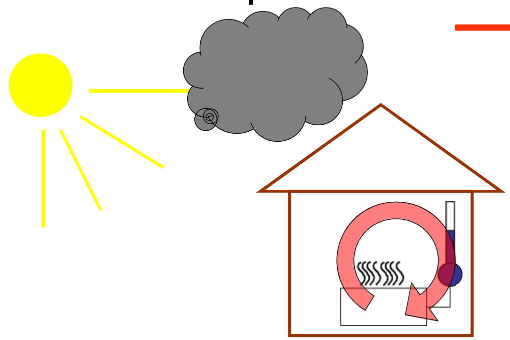
Open loop



Feed-forward



Closed loop - feedback



Content - some control ideas

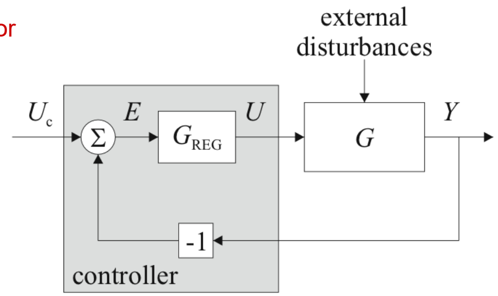
- Simple controllers – PID
- Cascade control
- State feedback
- Feed forward
- More advanced control

Feedback

- Concept of feedback used everywhere
  - Society
    - Economy – economic data is fed to ECB, which controls the interest rate in order to keep the inflation at a certain level
  - Nature
    - Human body – the nerve cells senses the temperature and the brain controls the muscles to restrict the skin capillaries
- Feedback – corrective action

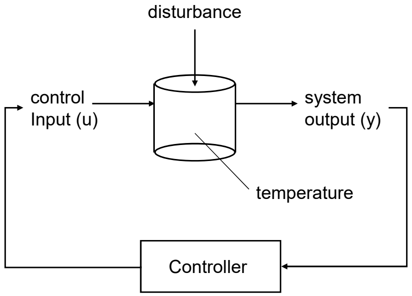
Feedback controller

The regulator problem

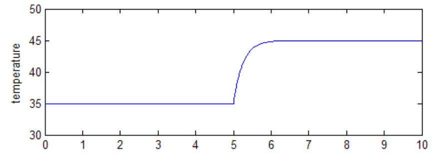


The servo problem

Test model – disturbance rejection

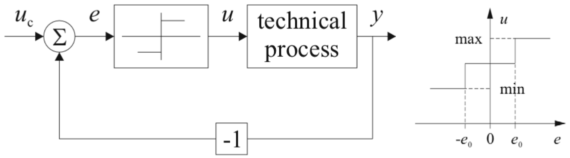


Without control

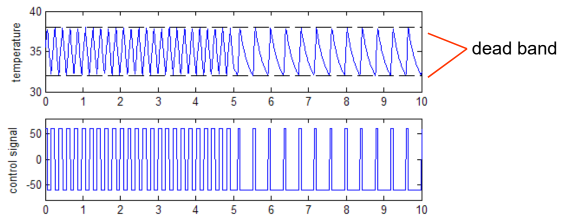


Disturbance imposed at time = 5

On-off controller



On-off control

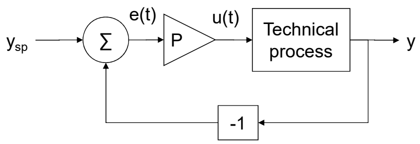


Used much in practice

e.g. level control

Very hard on equipment!

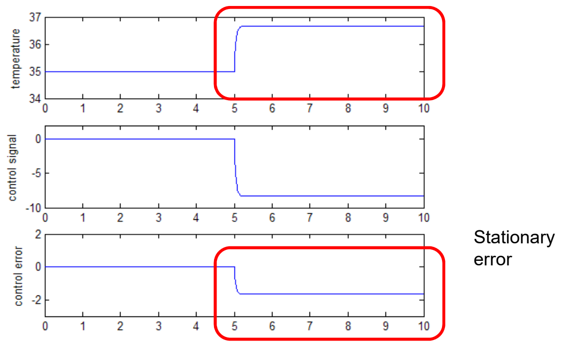
Proportional (P) control



$$u(t) = P \cdot e(t)$$

$$e(t) = y_{sp} - y$$

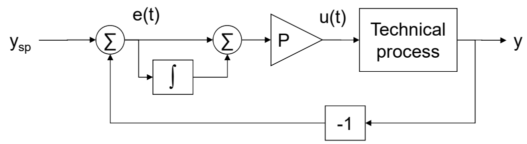
P-control



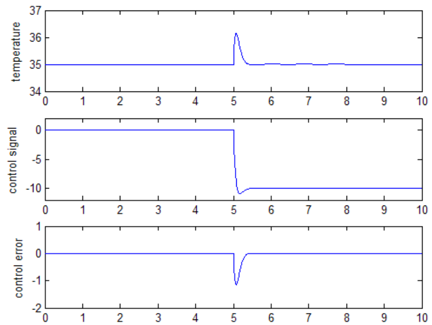
Stationary error

- When e => 0, u => 0
- One option: increase gain (P)
  - May lead to instability
- Better option: introduce integral action

Integral action



PI-control



Stationary error = 0

The PID controller

$$u = u_0 + K_P\left(e + \frac{1}{T_i}\int e\,dt + T_D\frac{de}{dt}\right)$$

Control signal

Off-set

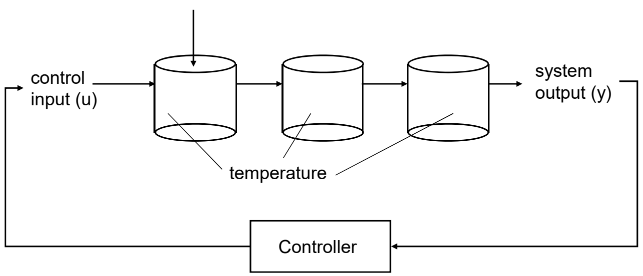
Proportional gain

Error y_{sp} - y

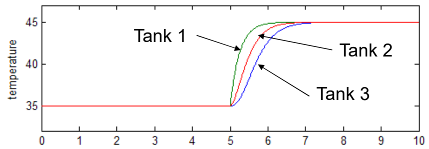
Integral time

Derivative time

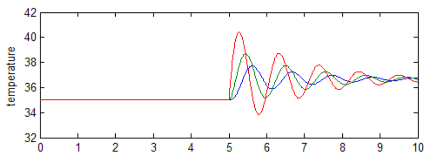
Test model – 3 tanks in series



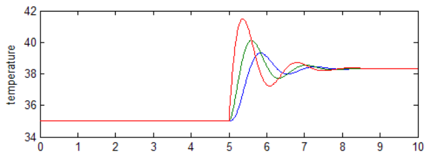
Tanks in series – no control



P-control

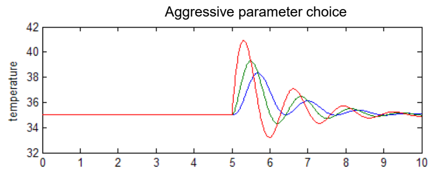


Same gain
as in 1-tank

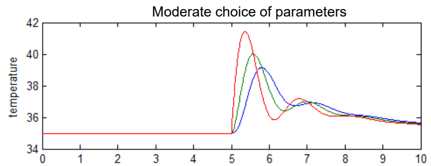


Smaller gain:
Larger stationary
error

PI-control

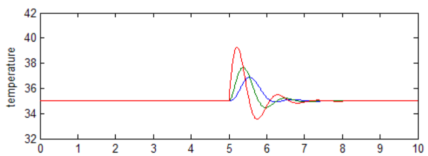


No stationary
error but
oscillating



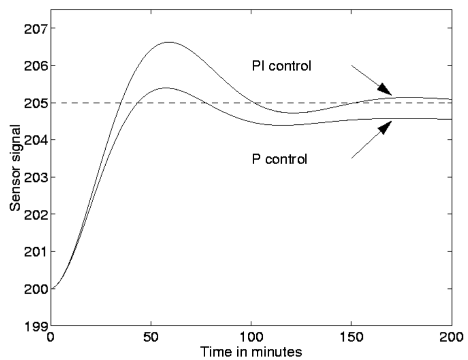
Less oscillating
but slow

PID-control

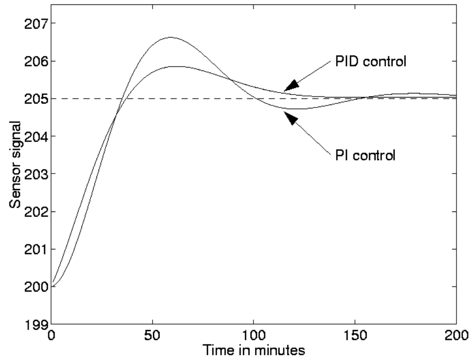


No (or marginal)
oscillations
but slow

P vs PI control – step change



PI vs PID control – step change



Ziegler Nichols tuning

1. Turn the controller to P-only mode, i.e. turn both the Integral and Derivative modes off.
2. Note if control gain is positive or negative.
3. Apply the input.
4. Change K in step increments and wait for a steady state.
5. Increase until sustained periodic oscillation and note the critical K_u
6. Note the period of the oscillation, P_u

Ziegler Nichols tuning

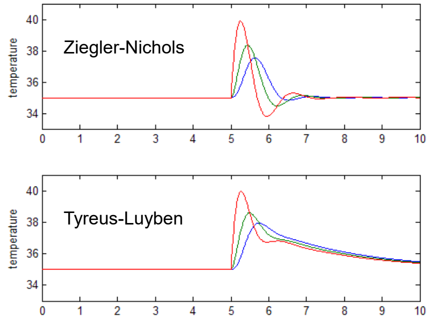
	K	T_i	T_d
P	$K_u/2$	-	-
PI	$K_u/2.2$	$P_u/1.2$	-
PID	$K_u/1.7$	$P_u/2$	$P_u/8$

Tyreus-Luyben Tuning

- Same procedure to find K_u and P_u
- Less aggressive – less oscillations

	K	T_i	T_d
P	$K_u/2$	-	-
PI	$K_u/3.2$	$2.2{\cdot}P_u$	-
PID	$K_u/2.2$	$2.2{\cdot}P_u$	$P_u/6.3$

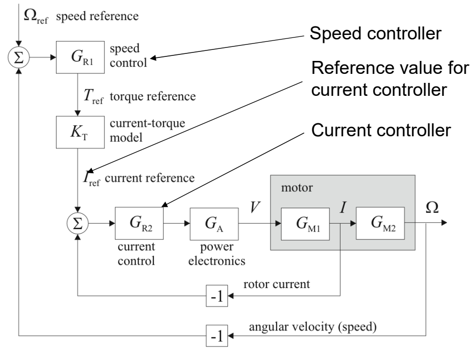
Tuning



Improving the performance

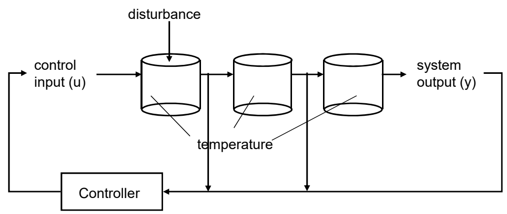
- Cascade control
- State feedback
- Feed-forward

Cascade control

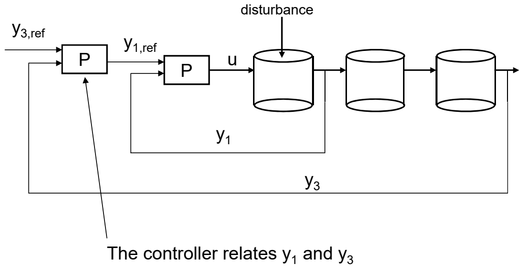


Cascade control

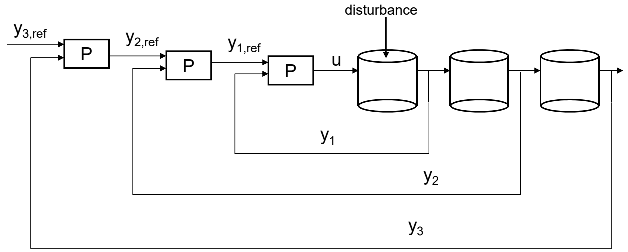
- Assume that we can measure in the test process



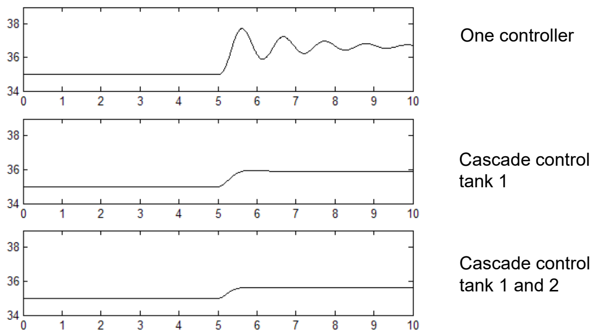
Cascade control



Cascade control



Cascade control

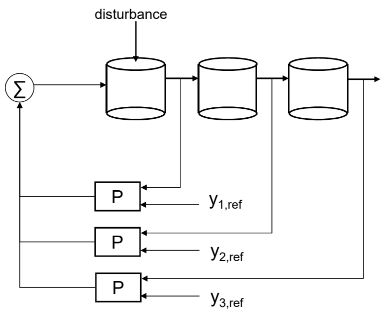


Cascade control

- The stationary error is easily removed by integral action on the outer loop
- Only one integral action
  - If the time constants of the loops are close they can start working against each other
- More than one integral action possible if the time constants are different
- In practice: the inner loops are typically sampled faster

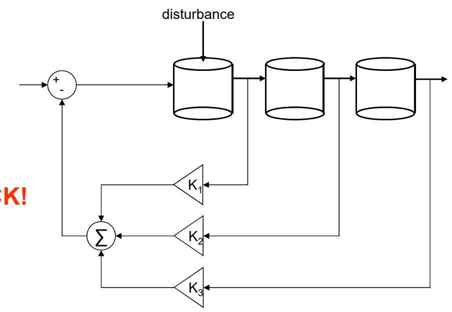
Cascade control alternative representation

Note: the parameters of the controllers are different from the other representation.



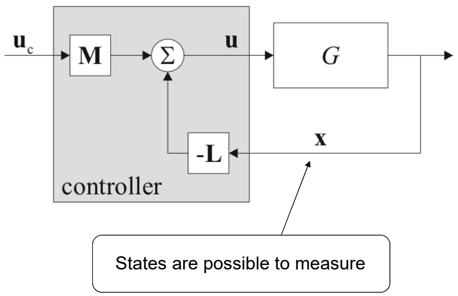
Cascade control alternative representation

$K_1 \cdot y_{1,ref} + K_2 \cdot y_{2,ref} + K_3 \cdot y_{1,ref}$



STATE FEEDBACK!

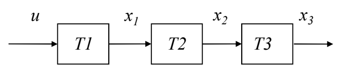
State feedback



State feedback (or cascade control)

- Feed back states to controller
- Pole placement used for controller design
  - Hand calculations for small (2nd order) systems
  - Matlab for larger systems
- If all states measurable
  - Control can be made fast (if no limits on the control action)
- Price: many sensors

Concentration in 3 tanks

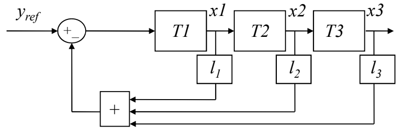


$$\dot{x} = Ax + Bu$$
$$y = Cx$$

State space description of the system

$$A = \begin{pmatrix} -\frac{q}{V_1} & 0 & 0 \\ \frac{q}{V_2} & -\frac{q}{V_2} & 0 \\ 0 & \frac{q}{V_3} & -\frac{q}{V_3} \end{pmatrix} \quad B = \begin{pmatrix} \frac{q}{V_1} \\ 0 \\ 0 \end{pmatrix}$$

State feedback 3 tanks in series



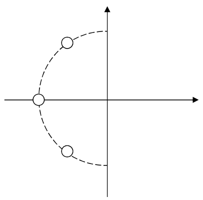
$$\dot{x} = (A - BL)x + By_{ref}$$

$$A - BL = \begin{pmatrix} -\frac{q}{V_1} - l_1\frac{q}{V_1} & -l_2\frac{q}{V_1} & -l_3\frac{q}{V_1} \\ \frac{q}{V_2} & -\frac{q}{V_2} & 0 \\ 0 & \frac{q}{V_3} & -\frac{q}{V_3} \end{pmatrix}$$

The eigenvalues of A-BL will determine the system

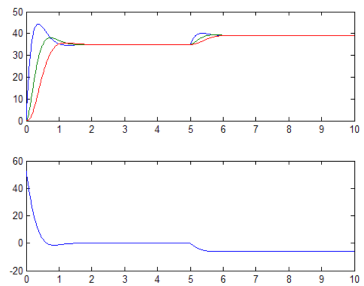
Example: control design

- Set L
  - Difficult to say anything of the system characteristics
- Pole placement
  - According to Butterworth – poles are placed on a circle
- Three cases
  - L = [0.5 0.5 0.5] => λ = [-6.9 -3.5+3.2i -3.5-3.2i]
  - λ = [-1 -0.5+0.86i -0.5-0.86i]·6 => L=[0 1.47 0.86]
  - λ = [-1 -0.5+0.86i -0.5-0.86i]·12 => L=[3.0 8.9 13.8]



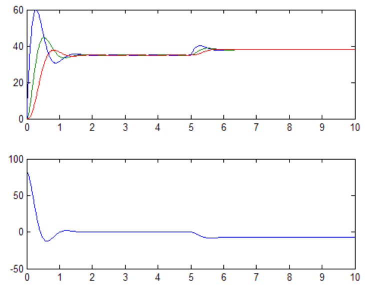
Example:

L = [0.5 0.5 0.5] => λ = [-6.9 -3.5+3.2i -3.5-3.2i]



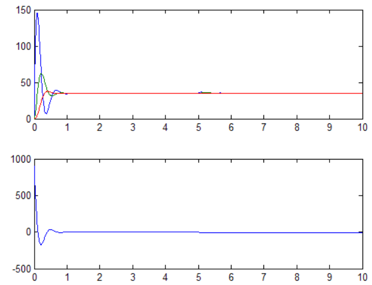
Example:

λ = [-1 -0.5+0.86i -0.5-0.86i]·6 => L=[0 1.47 0.86]



Example:

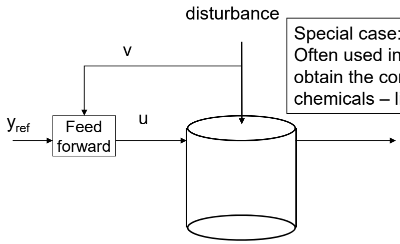
λ = [-1 -0.5+0.86i -0.5-0.86i]·12 => L=[3.0 8.9 13.8]



Feed-forward

- Measure the reference value or the disturbance before it hits the plant
- Compensate for the disturbance before it has affected the plant
- The price: must supply a model of the influence of the disturbance

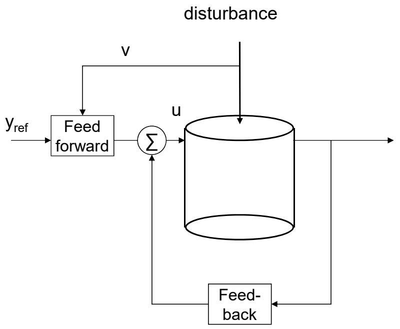
Feed forward



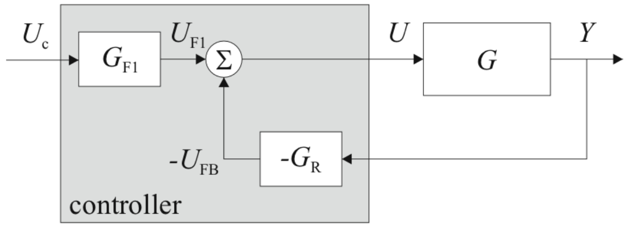
Special case: **Ratio control**
Often used in process control to obtain the correct addition of chemicals – like a recipe!

- No feedback – no guarantee that y_{ref} is achieved
- Need a perfect model between v and y
- Often sufficient for control

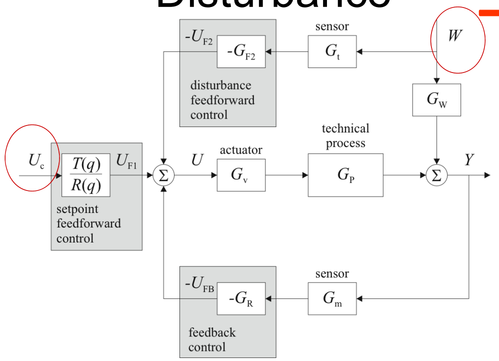
Feed forward + feedback



Feedforward from reference +feedback



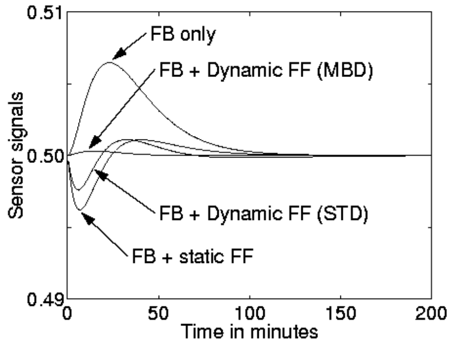
FF from both Ref and Disturbance



Feedforward design

- Measure dynamics of manipulated variable and disturbance
- Different sophistication level on model from disturbance to process (static, dynamic)
- Check realisability
  - Manipulated variable dynamics faster than disturbance dynamics
- Implement full or partial controller

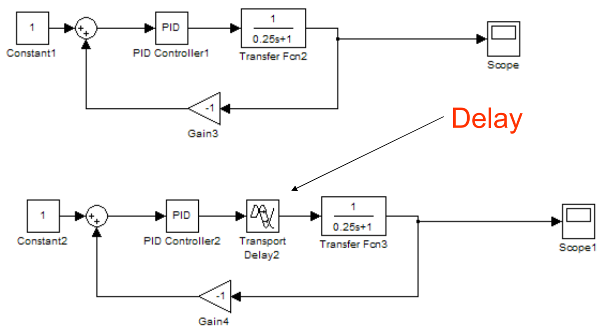
Feedforward performance



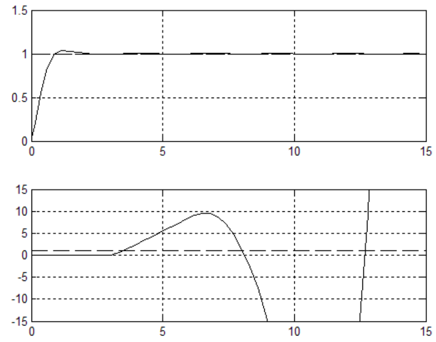
Time delays

- Time delays in the process
  - Delay in the physical process – transport, slow dynamics
  - Delay in the measurement of the variable
  - Delay in the control action
- May introduce oscillations
- Makes the control slow
  - Control parameters must be moderate

Time delays



Time delays



No delay

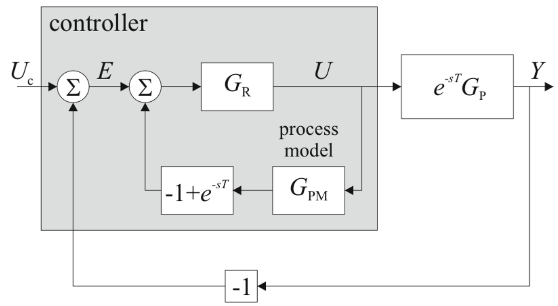
With delay (same control parameters)

Time delays

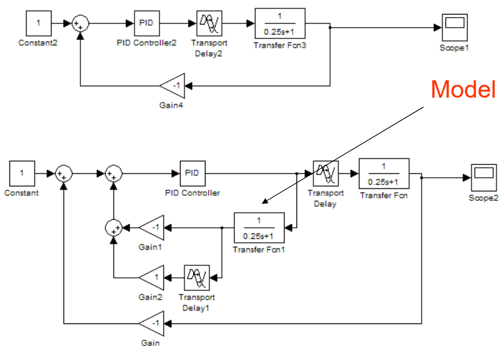
Solutions:

- Use moderate control parameters
  - Slow controller
- Use controller with delay compensation
  - Smith predictor
  - If model perfect – results the same as the response without delay but time lagged!

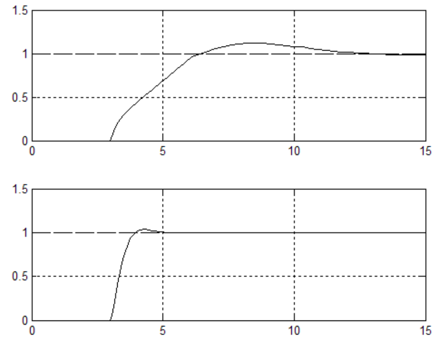
Smith predictor



Smith predictor



Smith predictor



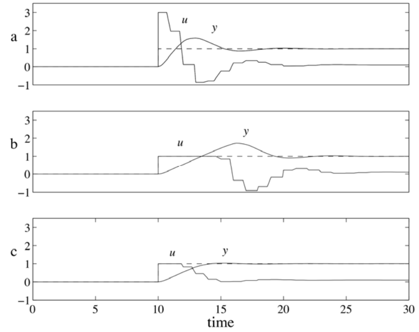
With delay (moderate control parameters)

With delay (Smith predictor)

Some practical limitations

- Control actions
  - Amplitude
  - Direction
- Measurement
  - States – are they possible to measure?
  - Disturbances – are they possible to measure?
  - Noise
- Time varying process
  - Process behaviour not constant

The windup problem



no limitation on *u*
→ no windup

limitation on *u*,
→ windup

limitation on *u*,
windup prevention

Changing the D part

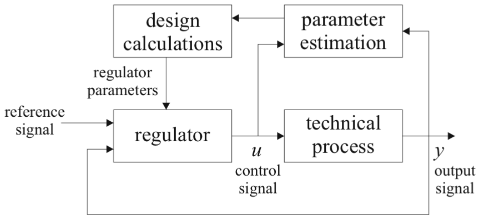
$$u = u_0 + K_P\left(e + \frac{1}{T_i}\int e\,dt - T_D\frac{dy}{dt}\right)$$

Noise filtering of the D part

$$-T_D\frac{dy}{dt} \;\rightarrow\; -T_D sY(s)$$

$$\rightarrow\; -T_D\frac{s}{1+T_f s}Y(s)$$

Adaptive controller



Predictive control

- General principle of operation:
  - use past control actions (and predicted disturbances) with the model to predict future measured variables
  - compare to the goals and constraints
  - determine appropriate control actions to take

Predictive control