Overview of lecture topics

- Topic 1: Course introduction
- Topic 2: Introduction to frequency domain and Laplace transformation
- Topic 3: Dynamic Behavior of Linear systems
- Topic 4: Frequency Response Analysis and Bode plots
- Topic 5: Mathematical Description of Chemical Systems
- Topic 6: Nonlinear ODE's, Linearity, Linearization, Feedback, Stability, Root Locus
- Topic 7: Feedback Controller Design and Bode stability
- Topic 8: Advanced (Enhanced) Process Control

Dynamics and Control of Processes

Lecture 8: Extensions to Basic Control Design

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Course 6E8X0

Extensions to Basic Control Design

- Deadtime compensation
- Split Range Control
- Cascade Control
- Feedforward Control
- Ratio Control
- Selective Control
- Override Control
- Inferential Control

Extensions to Basic Control Design

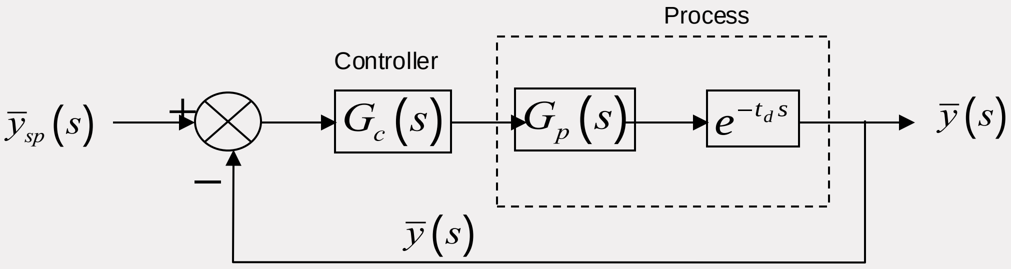
Deadtime Compensation

- Controlling processes with large dead time (relative to the time constant of the process) by pure feedback alone is difficult
  - Effect of disturbances is not seen by controller for a while
  - Effect of control action is not seen at the output for a while. This causes controller to take unnecessary compensation.
  - Delays add phase lag to the feedback loop hence is a source of instability for the closed loop.

Extensions to Basic Control Design

Deadtime Compensation

- Example



Processes

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

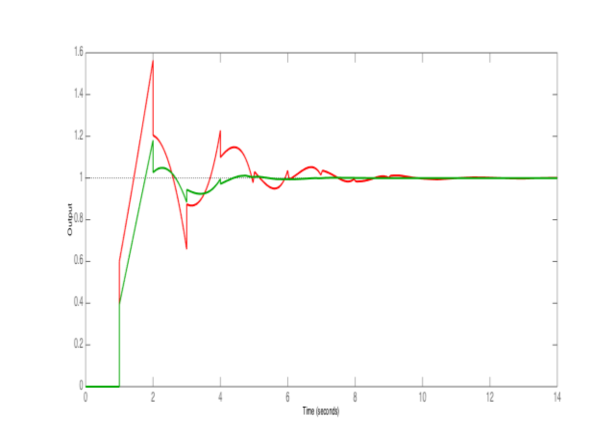
$$G_p(s) = \frac{2}{4s+1}e^{-8s}$$

- Exercise: Compare the closed loop response of PID controller with reaction curve tuning and IMC tuning.

Extensions to Basic Control Design

Deadtime Compensation

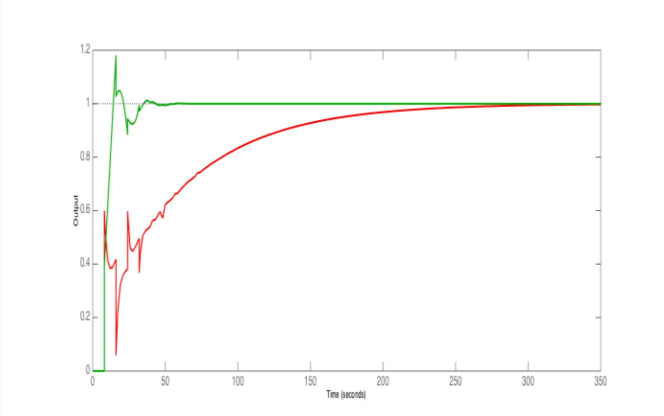
- Exercise



PID Controller,

Z-N tuning: $K_c = 1.2$, $T_i = 4$min, $T_d = 1$ min

IMC tuning: $K_c = 1.96$, $T_i = 2.5$ min , $T_d = 0.4$ min



PID Controller,

Z-N tuning: $K_c = 0.3$, $T_i = 16$ min, $T_d = 4$ min

IMC tuning: $K_c = 0.39$, $T_i = 8$ min , $T_d = 2$ min

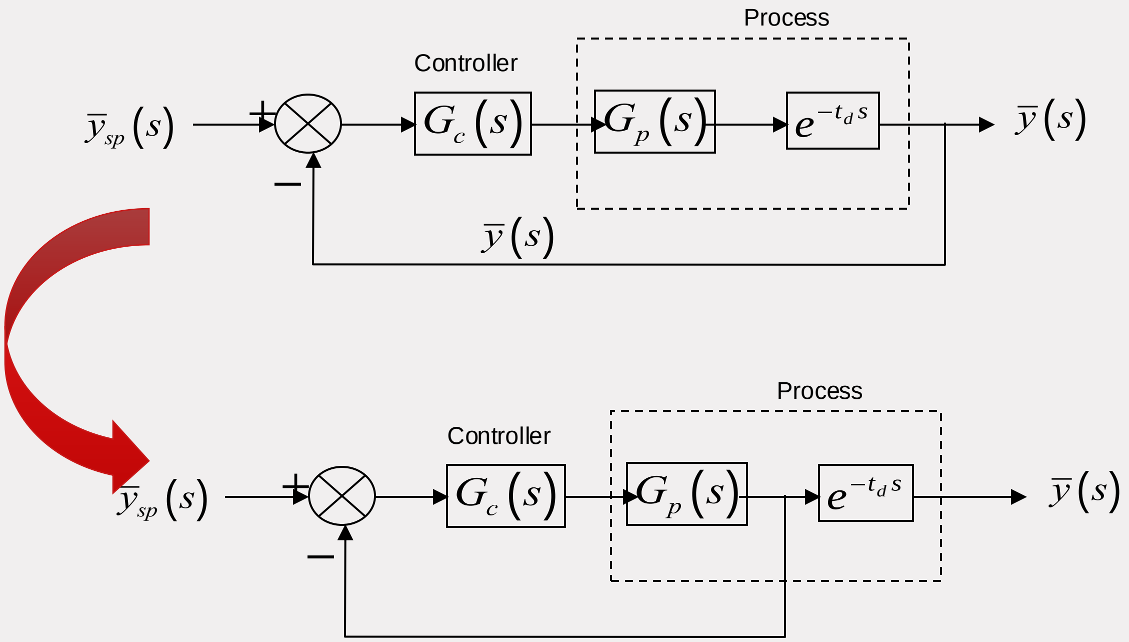
Extension to Basic Control Design

Deadtime Compensation

- What Causes Deadtime?
  - Transportation lag (long pipelines)
  - Sampling downstream of the process
  - Recycle loops
  - Slow measuring device: GC
  - Large number of first-order time constants in series (e.g. distillation column)
  - Sampling delays introduced by computer control

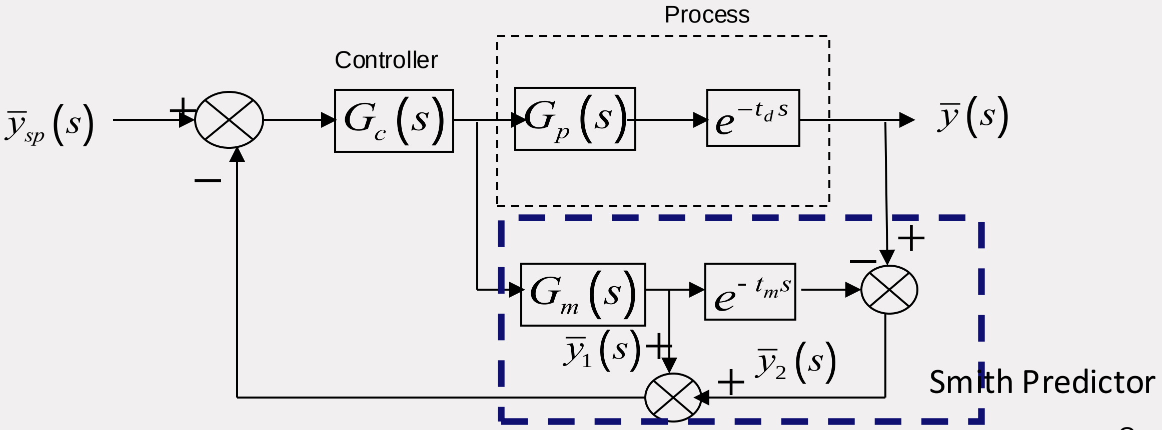
Extensions to Basic Control Design

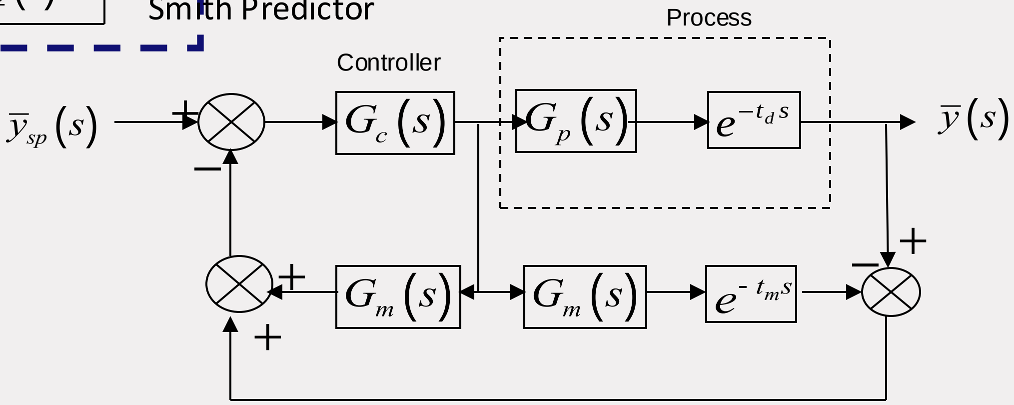
Deadtime Compensation-Smith Predictor (1957)



Extensions to Basic Control Design

Deadtime Compensation-Smith Predictor (1957)

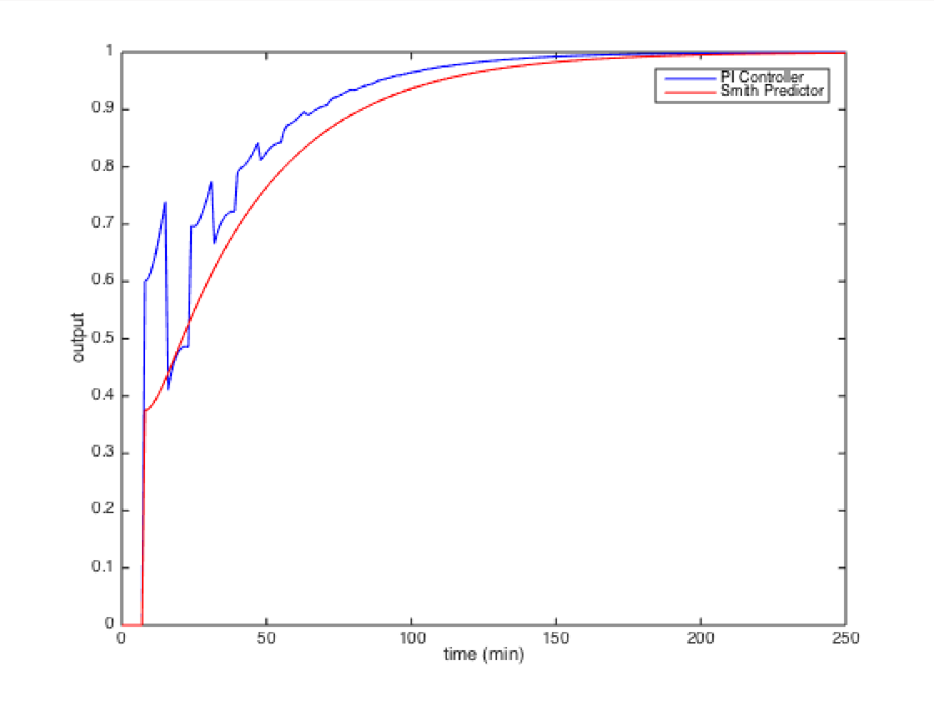




Extensions to Basic Control Design

Deadtime Compensation

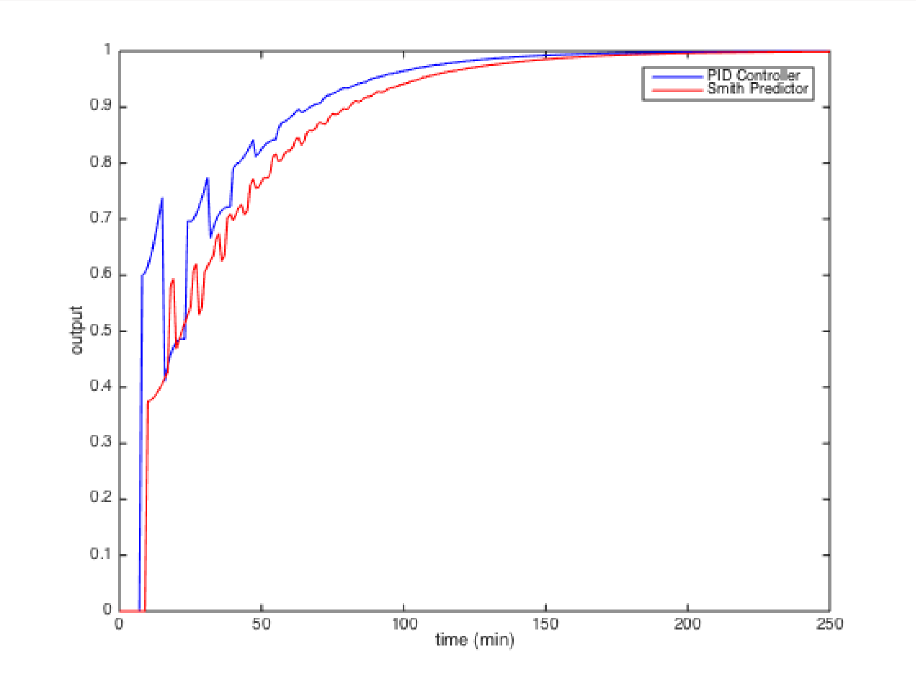
- Exercise: Smith predictor with Accurate Model



Extensions to Basic Control Design

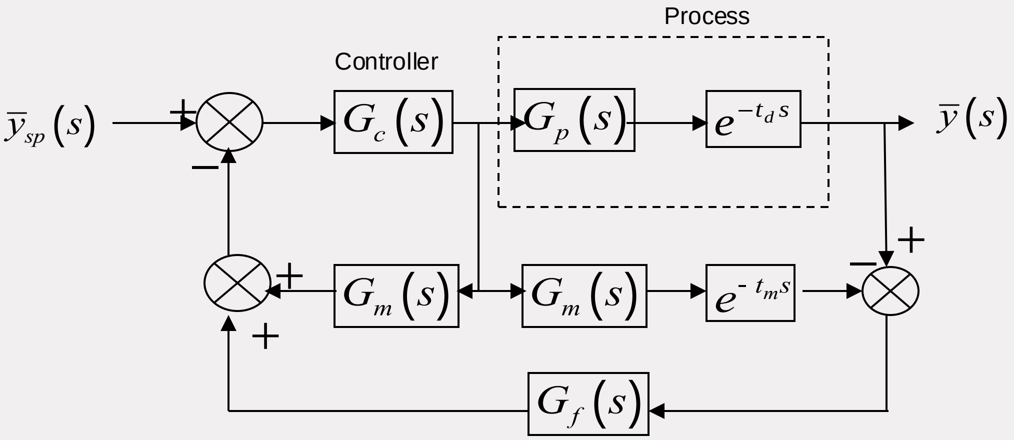
Deadtime Compensation

- Exercise: Smith predictor with Less Accurate Model



Extensions to Basic Control Design

Deadtime Compensation-Smith Predictor (1957)



Prediction Error Filter

$$G_f(s) = \frac{1}{\tau s + 1}$$

Extensions to Basic Control Design

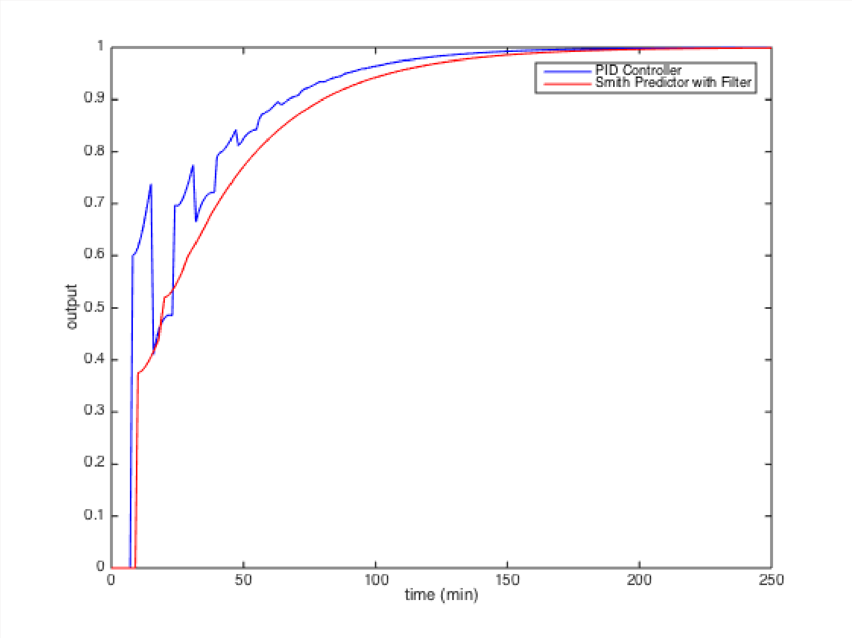
Deadtime Compensation

- Exercise: Improved Smith predictor with Less Accurate Model

$$G_m(s) = \frac{2.0}{4s+1}e^{-8s};$$

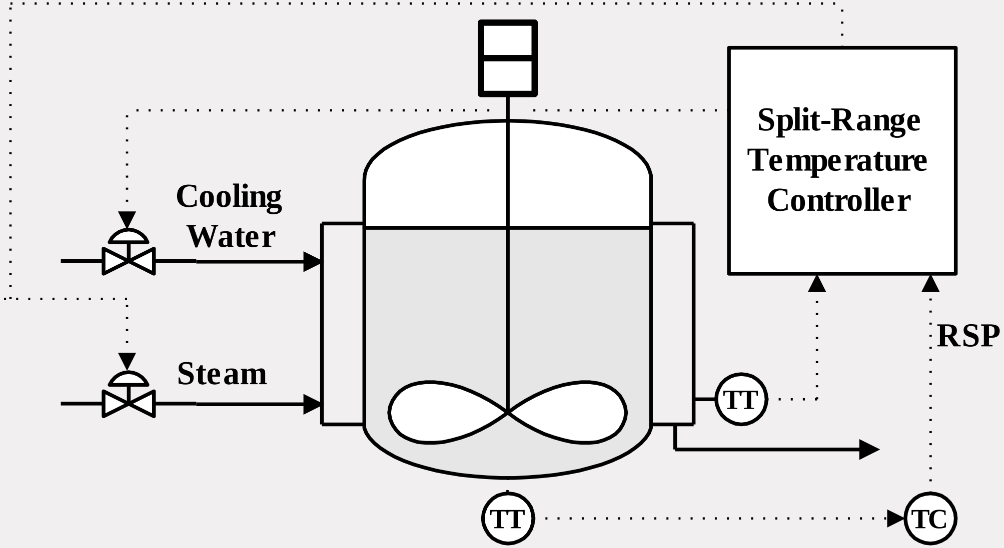
$$G_p(s) = \frac{2.0}{4s+1}e^{-10s};$$

$$G_f(s) = \frac{1}{4s+1}$$



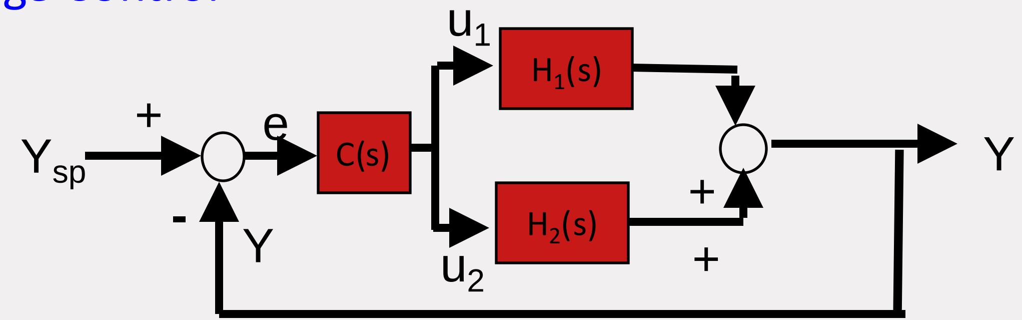
Extensions to Basic Control Design

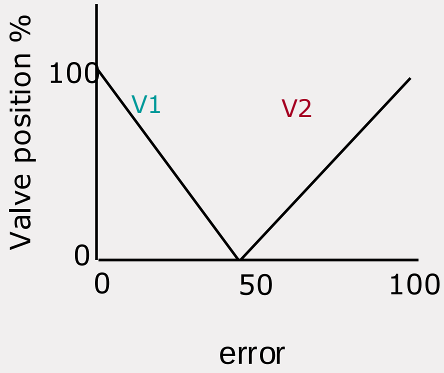
Split Range Control



Extensions to Basic Control Design

Split Range Control



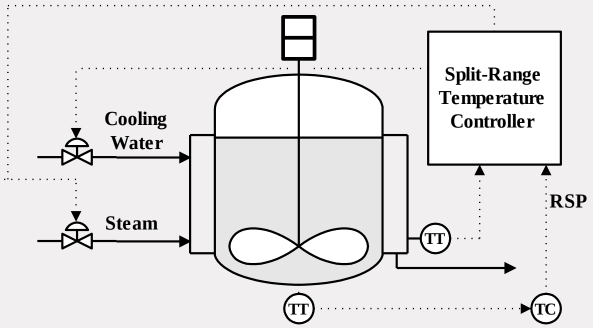


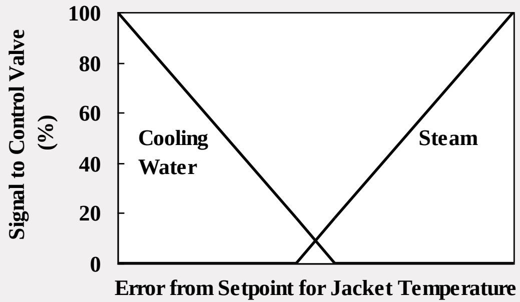
- One controlled output
- More than one manipulated variable
- Closed loop system changes depending on u_1 or u_2

Extensions to Basic Control Design

Split Range Control

Example





Extensions to Basic Control Design

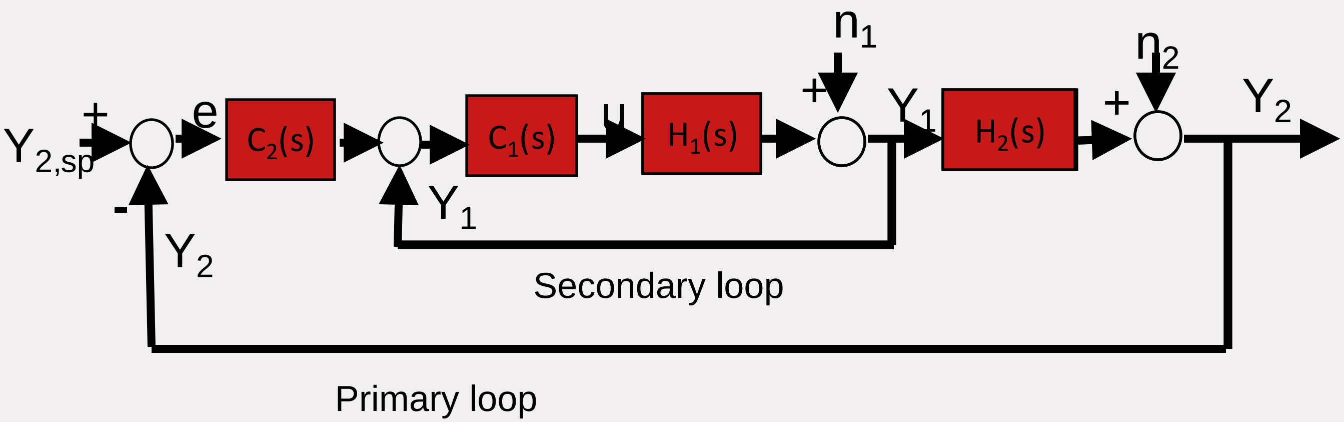
Cascade Control

- If the single feedback control loop has poor performance, the performance can be improved by controlling a second variable with the following properties.
  - It is affected by a disturbance or a process parameter variation which causes poor control of the primary variable.
  - It is affected by the manipulated variable used to control the primary variable
  - Its dynamics is faster than the dynamics of the primary variable.
- If these criteria are satisfied, cascade control can improve the controlling the primary variable.
  - the secondary variable is controlled by a secondary (or slave) controller, which receives its setpoint from
  - a primary (or master) controller controlling the primary variable

Extensions to Basic Control Design

Cascade Control

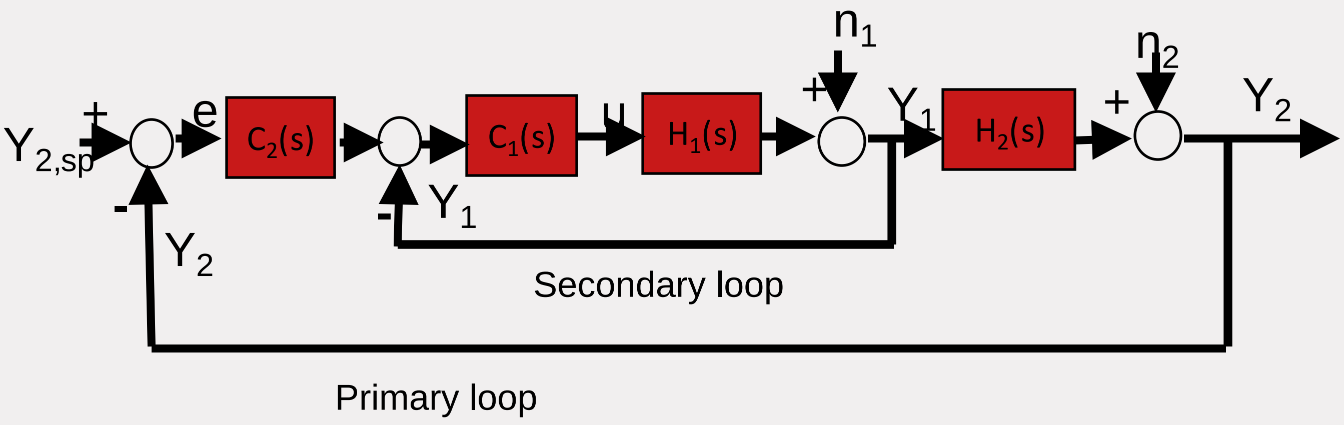
Two processes in series



- Two feedback controllers but one manipulated variable
- Output of the primary loop is the setpoint for the secondary loop
- Disturbances to the secondary loop are corrected

Extensions to Basic Control Design

Cascade Control



$$Y_2(s) = \frac{C_2(s)C_1(s)H_1(s)H_2(s)}{1+C_1(s)H_1(s)+C_2(s)C_1(s)H_1(s)H_2(s)}Y_{2,sp}(s) + \frac{H_2(s)}{1+C_1(s)H_1(s)+C_2(s)C_1(s)H_1(s)H_2(s)}n_1(s)+$$
$$\frac{1+C_1(s)H_1(s)}{1+C_1(s)H_1(s)+C_2(s)C_1(s)H_1(s)H_2(s)}n_2(s)$$

Extensions to Basic Control Design

Cascade Control

- Analysis
  - Consider the two limiting cases

1. No secondary controller (C1(s)=1, no secondary feedback)

$$Y_2(s)=\frac{C_2H_1H_2}{1+C_2H_1H_2}Y_{2,sp}(s)+\frac{H_2}{1+C_2H_1H_2}n_1(s)+\frac{1}{1+C_2H_1H_2}n_2(s)$$

1. Secondary controller is perfect ($Y_{1ref}=Y_1$)

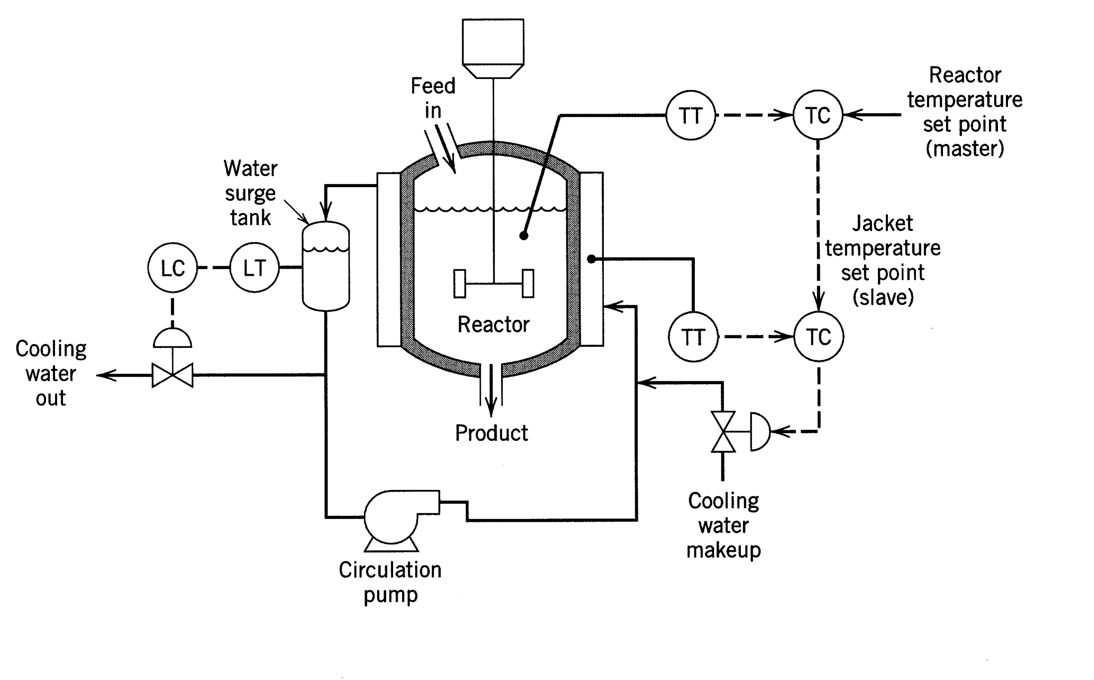
$$Y_2(s)=\frac{C_2H_2}{1+C_2H_2}Y_{2,sp}(s)+\frac{1}{1+C_2H_2}n_2(s)$$

What are the advantages?

Extensions to Basic Control Design

Cascade Control

Example: Cascade control of exothermic chemical reactor



Extensions to Basic Control Design

Cascade Control

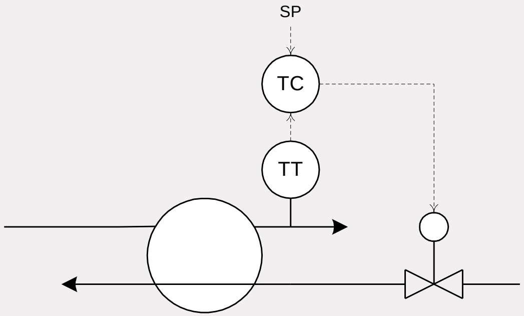
- Disturbances in the secondary loop are corrected by the secondary.
- Phase lag existing in $H_1(s)$ is reduced by the secondary loop
- Gain variations in H_1 are overcomed within its own loop
- Design/tuning
  - First design C_1(fast loop) to reject n_1
  - Then design C_2 to reject n_2

Extensions to Basic Control Design

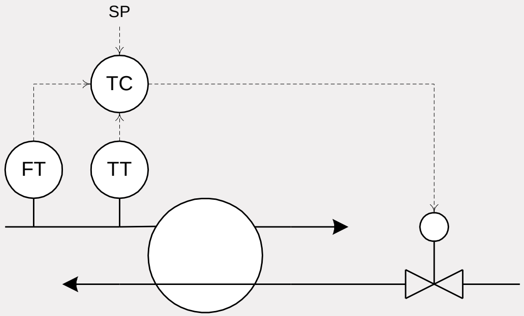
Feedforward Control

In case of feedback control, the controlled variable and its reference are used to determine the input to the process.

In case of feedforward control, the reference and disturbances are used to determine the input of the process.



Feedback

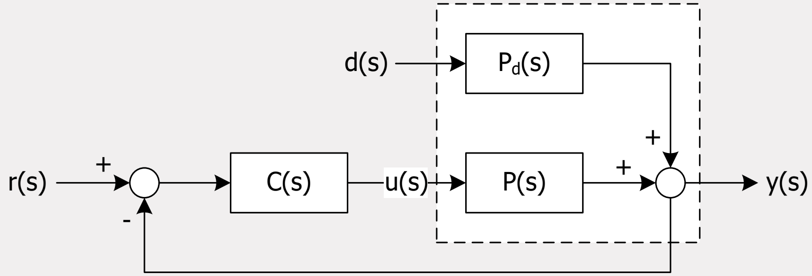


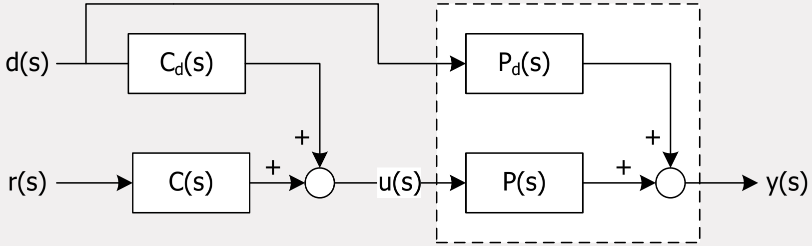
Feedforward

Extensions to Basic Control Design

Feedforward Control

Feedback and feedforward…





Extensions to Basic Control Design

Feedforward Control

The closed-loop transfer functions are given by:

$$y(s) = \frac{P_d(s)}{1+P(s)C(s)} d(s) + \frac{P(s)C(s)}{1+P(s)C(s)} r(s)$$

$$y(s) = \left(P_d(s) + P(s)C_d(s)\right) d(s) + P(s)C(s)r(s)$$

These transfer functions have three important implications:

1. Stability: in case of feedback, the poles of the controlled system are given by 1 + P(s)C(s) = 0 while for feedforward control the poles are just the poles of P(s), P_d(s) and C(s). In other words feedback control can affect the stability (in positive or negative sense) while feedforward control can not.

Extensions to Basic Control Design

Feedforward Control

Robustness: For good reference tracking, the transfer function before r(s) should be equal to 1. In case of feedback, this means that P(s)C(s) should be large. In case of feedforward, $C_d(s)$ should be equal to $-P_d(s)/P(s)^{-1}$. This argumentation can be extended to disturbance rejection. Therefore, feedforward control requires a much better process model than feedback control does.

Speed: For feedback action $r(s) - y(s) \neq 0$, thus a disturbance has to affect first y(s) before any control action is taken. So, feedforward control is faster than feedback control.

Extensions to Basic Control Design

Feedforward Control

	Stability	Robustness	Speed
Feedback	Can change	High	Limited
Feedforward	Does not change	Low	High

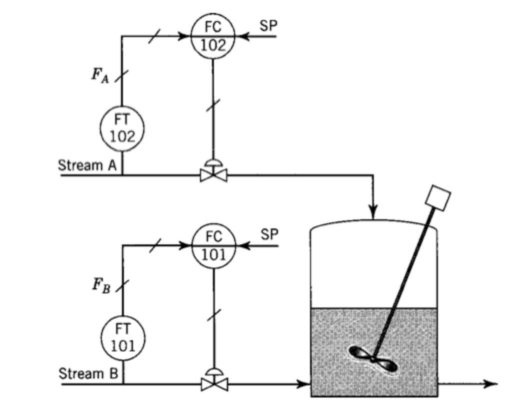
So feedback and feedforward are complementary. Therefore, it makes sense to apply both. Normally one starts with feedback control and extends it with feedforward if necessary.

Why should we start with feedback control?

Extensions to Basic Control Design

Ratio Control

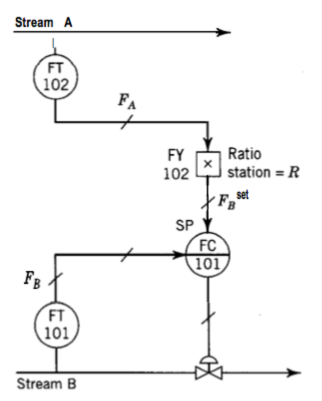
- It is a simple version of feedforward control,
- The effect of disturbances is counteracted by maintaining a fixed ratio between two variables (one of which is the disturbance)
  - Blending problems
  - The ratio between reflux and distillate

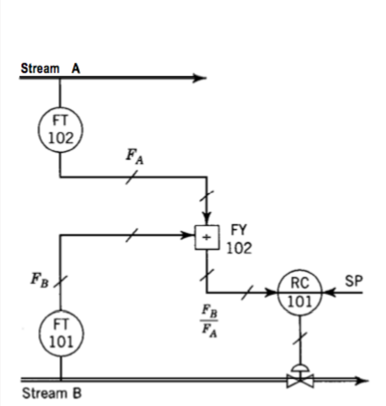


$R=F_B/F_A$

Extensions to Basic Control Design

Ratio Control





Error=F_{Bset}-RF_A

Control performance will not vary with F_A

Error=R-F_B/F_A

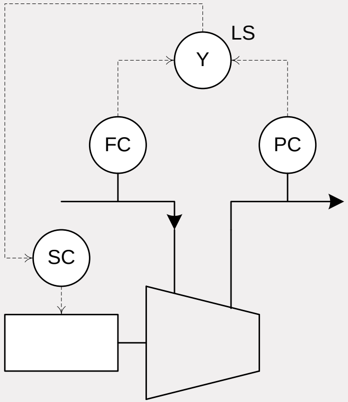
Control performance will vary with F_A

Extensions to Basic Control Design

Override Control

Override: There are two control objectives but only one DOF (can be seen as SIMO). Only one controller is active, the other one “waits” until the PV gets above or below the SP.

A typical example is FC/PC control of a compressor.

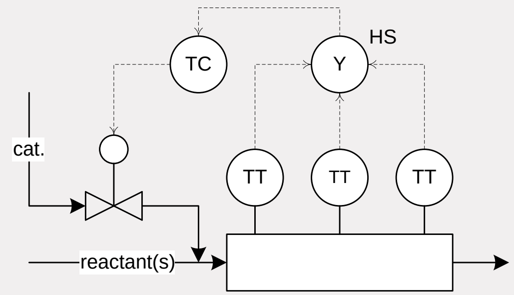


Extension to Basic Control Design

Selective Control

Selective: from a number of available measurements one is selected as the control objective (SIMO, distributed).

Typical examples are temperature profile control of a tubular reactor and redundant measurement control (for example middle out of three).



Extensions to Basic Control Design

Inferential Control

Inferential: If it is expensive or even impossible to measure what needs to be controlled then it is inferred (read calculated) from other measurements (direct calculation / observer).

A typical example is a pressure temperature calculation to infer the quality on a specific tray in a distillation column.