Chemical Process Control

Topic 14 (cont.)

Advanced Control Strategies

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Last time we saw:

- Advanced control structures can significantly improve control performance
  - **Cascade** - can effectively remove certain disturbances if the slave loop is at least 3 times faster than the master loop.
  - **Ratio control** - is effective for processes that scale with the feed rate.
  - **Feedforward** - can be effective for measured disturbances for slow responding processes as long as the process nonlinearity is not too great.

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Objectives for Today

- Other advanced control strategies:
  - Smith predictor (dead time compensation)
  - Internal Model Control (IMC)
  - Model Predictive Control
  - Real time optimization

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Time-delay systems

- Control Problems:
  - Output delay - with a delay (e.g. in the measuring device) control action will be based on obsolete process information that is usually not representative to the current situation
  - Input delay – (e.g. because of transport delay) then the effect of the control action will not be immediately felt by the process
- These situations can provoke instability
- It is important to compensate the effect of time delays in closed-loop control

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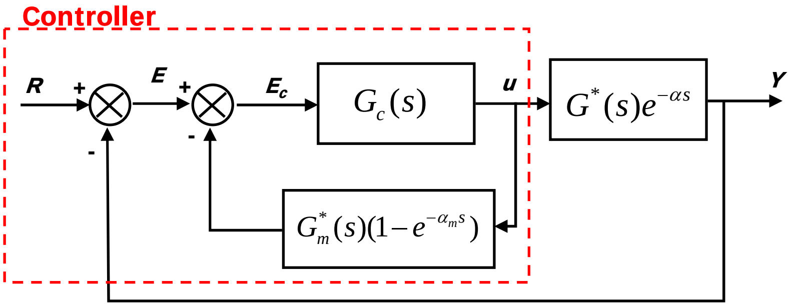
Dead-time compensation (Smith Predictor)

- Consider general process transfer function with time delay, and corresponding model transfer function:

$$G_p(s) = G^*(s)e^{-\alpha s} \qquad G_m(s) = G_m^*(s)e^{-\alpha s}$$

Transfer function with "normal" (undelayed) dynamics



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Dead-time compensation (Smith Predictor)

- Consider general process transfer function with time delay, and corresponding model transfer function:

$$Y^* = G^*(s)u \qquad Y_m^* = G_m^*(s)u$$

"Undelayed" output

$$Y = G^*(s)e^{-\alpha s}u$$

No model errors: $G_m(s) = G(s)$ $\qquad \alpha_m = \alpha$

"Corrected" error signal: $E_c = R - Y - (Y^* - Y)$ or $E_c = R - Y^*$

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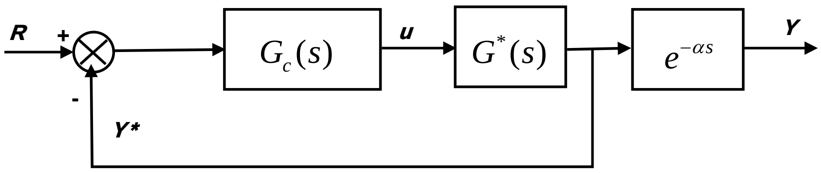
Dead-time compensation (Smith Predictor)

- Results imply that the previous block diagram is equivalent to the diagram below
- Time-delay factor is "moved" outside the feedback loop where has no effect on the closed-loop system stability
- Characteristic equation:

$$1 + G_c(s)G^*(s) = 0$$

- No longer contains time delay element → allows the use of higher controller gains



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Dead-time compensation (Smith Predictor) – Important features

- Compensator (inner loop) moves time-delay outside closed-loop
- Effective action of the compensator is to feed the signal Y* to the controller instead of the actual process output
- From previous equations we see

$$Y^* = e^{\alpha s}Y(s) \qquad \Rightarrow \qquad Y^*(t) = Y(t+\alpha)$$

Y^* is a prediction of $Y(t)$ exactly α time units ahead ("Smith predictor")

- The scheme works perfectly as long as the process model is perfectly known; modelling errors affect the performance (Smith predictor is sensitive to modelling errors)
- Smith predictor is design for systems with constant time delay, hence may not performe well for systems with time delays that vary significant over time (e.g. in transport processes through long pipes time delay varies with flow rate)

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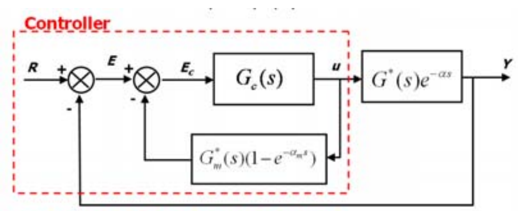
Dead-time compensation (Smith Predictor) – Design Procedure

❶ Using open-loop experiments derive the model as a FOPDT system:

$$G_m(s) = \frac{1}{\tau s + 1} e^{-\alpha_m s}$$

❷ By means of appropriate hardware, implement the controller portion of the block diagram of the Smith predictor



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Internal Model Control (IMC)

- Modern control strategy (intensive research and growing application since 1980s)
- Controller design method based on accurate process model
- Provides controller which is stable and robust (maintains stability under varying conditions)

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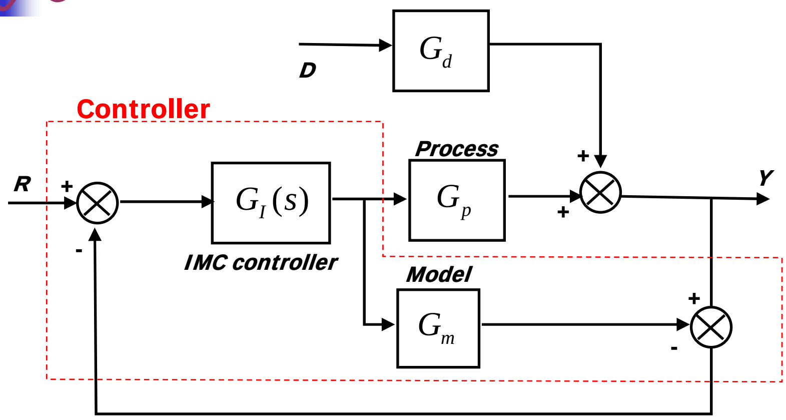
Block diagram of IMC



Similar structure as the Smith predictor

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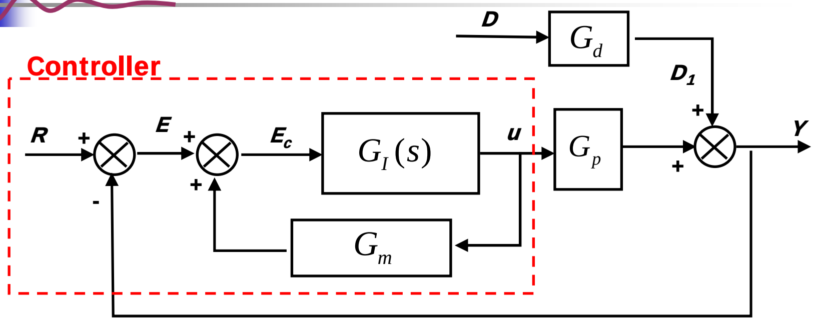
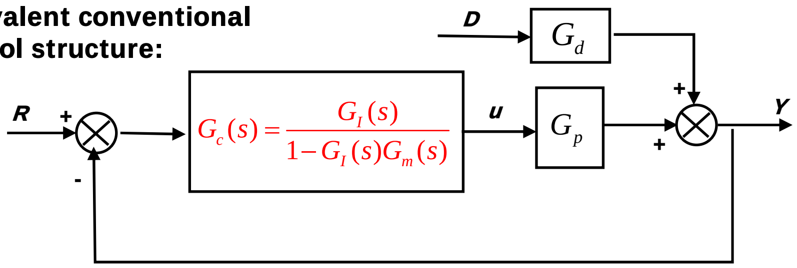
Block diagram of IMC - Rearranged



Equivalent conventional control structure:



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IMC - Properties

- Transfer function for the generic IMC based feedback control:

$$G_c(s) = \frac{G_I(s)}{1 - G_I(s)G_m(s)}$$

- Closed loop response

$$Y = D_1 + \frac{G_p G_I}{1 + G_I(G_p - G_m)}(R - D_1)$$

IMC - Properties

- When the model exactly matches the process: $G_m = G_p$

$$Y = D_1 + \frac{G_p G_I}{1 + G_I(G_p - G_m)}(R - D_1) \qquad \Rightarrow Y = D_1 + G_p G_I (R - D_1)$$

= 0

- For only setpoint change (D_1 = 0) we want $Y = R$

$$G_I = \frac{1}{G_m}$$

- For only change in disturbance (R = 0) we want the output undisturbed $Y = 0$

$$G_I = \frac{1}{G_m}$$

- *IMC controller should be the inverse of the transfer function of the process model (when no model plant mismatch)*

IMC - Properties

- Application of G_I=1/G_m leads to transfer functions which cannot be implemented (are unstable, requires prediction, or pure derivative action)
- For simple first order model for example

$$G_m = \frac{1}{\tau s + 1} \quad \Rightarrow \quad G_I = \tau s + 1$$ → Pure lead system

- For FOPDT model:

$$G_m = \frac{e^{-\alpha s}}{\tau s + 1} \quad \Rightarrow \quad G_I = (\tau s + 1)e^{\alpha s}$$ → $e^{\alpha s}$ represent prediction

- For a transfer function with zero:

$$G_m = \frac{1 - s}{\tau s + 1} \quad \Rightarrow \quad G_I = \frac{\tau s + 1}{1 - s}$$ → RHP pole → unstable

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IMC Design

❶ Separate the process model G_m into two terms

$$G_m = G_+ G_-$$

Where G_+ contains all the noninvertible aspects (delay, RHP zeros), with a gain equal 1, and G_- is the remaining invertible part

❷ Controller specification and filter design. The controller is specified as

$$G_I = \frac{f(s)}{G_-}$$ Where $f(s)$ is the filter usually of the form: $$f(s) = \frac{1}{(\lambda s + 1)^n}$$

With parameters λ and n to ensure that $G_I(s)$ is proper (numerator order is ≤ to denominator order

❸ Equivalent Conventional Controller form. If necessary, the IMC controller can be converted to the conventional form by using the equation for $G_c(s)$

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Example 1: IMC Design for a first order process

- Using the IMC strategy design a controller for the first-order process whose transfer function if given below. Convert this controller to the conventional feedback form

$$G_p(s) = \frac{5}{8s+1}$$

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Example 1: IMC Design for a first order process - SOLUTION

- The transfer function is completely invertible:

$$G_+(s) = 1 \quad and \quad G_-(s) = \frac{5}{8s+1}$$

- $G_-(s)$ requires only a first order filer (n = 1) in order that $G_I = f(s)/G_-(s)$ be proper:

$$G_I(s) = \frac{f(s)}{G_-(s)} = \frac{1}{\lambda s+1}\frac{8s+1}{5} = \frac{1}{5}\left(\frac{8s+1}{\lambda s+1}\right)$$

Can be implemented using a lead/lag element

- The conventional feedback form:

PI controller whose gain depends on λ

$$G_c(s) = \frac{G_I(s)}{1-G_I(s)G_m(s)} = \frac{\frac{1}{5}\frac{8s+1}{\lambda s+1}}{1-\frac{1}{5}\frac{8s+1}{\lambda s+1}\frac{5}{8s+1}} = \frac{8}{5\lambda}\left(1+\frac{1}{8s}\right)$$

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Example 2: IMC design for a FOPDT process

- Design an IMC controller using first order filter for the following FOPDT process

$$G_p(s) = \frac{5e^{-3s}}{8s+1}$$

Example 2: IMC design for a FOPDT process - SOLUTION

- Introduce first order Pade approximation for delay:

$$e^{-3s} = \frac{1-1.5s}{1+1.5s}$$

- The process model becomes:

$$G_m(s) = \frac{5}{8s+1} \times \frac{1-1.5s}{1+1.5s}$$

- Factor the resulting transfer function in G_+ and G_-:

$$G_+(s) = 1-1.5s \qquad G_-(s) = \frac{5}{(8s+1)(1.5s+1)}$$

Noninvertable part (RHP zero)

Example 2: IMC design for a FOPDT process - SOLUTION

- Choose first order filter: $f(s) = \dfrac{1}{\lambda s + 1}$

- The IMC controller will be:

$$G_I(s) = \frac{f(s)}{G_-(s)} = \frac{1}{\lambda s+1} \times \frac{(8s+1)(1.5s+1)}{5} = \frac{(8s+1)(1.5s+1)}{5(\lambda s+1)}$$

- The equivalent feedback controller is:

$$G_c(s) = \frac{G_I(s)}{1 - G_I(s)G_m(s)} = \frac{\dfrac{(8s+1)(1.5s+1)}{5(\lambda s+1)}}{1 - \dfrac{\cancel{(8s+1)}\,\cancel{(1.5s+1)}}{5(\lambda s+1)} \times \dfrac{5}{\cancel{8s+1}} \times \dfrac{1-1.5s}{\cancel{1+1.5s}}} = \frac{(8s+1)(1.5s+1)}{5(\lambda s+1) - 5(1-1.5s)}$$

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Example 2: IMC design for a FOPDT process - SOLUTION

- The equation is rearranged into:

$$G_c(s) = \frac{G_I(s)}{1 - G_I(s)G_m(s)} = \frac{(8s+1)(1.5s+1)}{5(\lambda s+1) - 5(1-1.5s)} = \frac{1}{5}\frac{(8s+1)(1.5s+1)}{\lambda s+1-1+1.5s} = \frac{1}{5}\frac{12s^2+9.5s+1}{(\lambda+1.5)s}$$

$$G_c(s) = \frac{1}{5}\frac{12s^2+9.5s+1}{(\lambda+1.5)s} = \frac{9.5}{5(\lambda+1.5)}\left(1 + \frac{1}{9.5}\frac{1}{s} + \frac{12}{9.5}s\right)$$

PID controller with τ_I = 9.5 and τ_D= 1.26 and K_c that depends on λ

- **Using the IMC design we only need to choose one design parameter, λ, for the PID controller!**

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Model Predictive Control (MPC)

- State-of-the-art in Process Control
- MPC = Repeated optimal control
- Every sampling period t_k solve an optimal control problem:

$$\min_{u(\cdot)} \mathcal{H}(x(t), u(t))$$

subject to:

- Model $\dot{x}(t) = f(x(t), u(t))$
- Measurement $y(t) = g(x(t), u(t))$
- Initial cond. $x(t_k) = \hat{x}(t_k)$
- Constraints $h(x(t), u(t)) \leq 0, \quad t \in [t_k, t_F]$

- Model can be linear (LMPC) or nonlinear (NMPC)
- LMPC well established in industry (in DMC)
- NMPC is the future

MPC - Main Idea

Obtain measurements y

↓

Estimate state x

↓

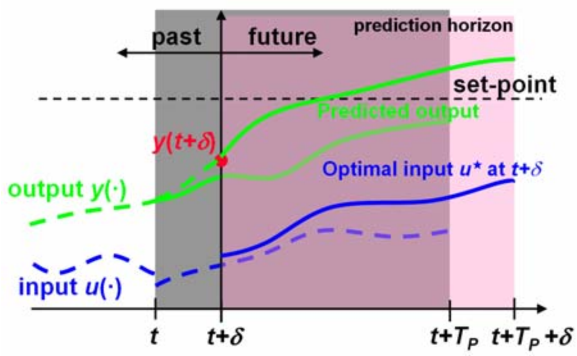
Solve optimal control problem:

$$\min_{u(t)\in\mathcal{U}} \mathcal{H}(x(t), u(t), p)$$

Subject to: model equations
constraints

↓

Implement input u



- **Based on objective:**
  - **Receding or shrinking horizon NMPC**

MPC: advantages & pitfalls

- Explicit incorporation of process model (including nonlinearities and multiple variables)

  → highly nonlinear processes, batch process control, ...
- Constraints are directly incorporated into formulation
- Straightforward formulation of economic objectives
- Considers future horizon
- Improved control performance due to better models

- Requires good process model
- High computational burden, delay
- Output feedback (need to "estimate initial condition for next integration of process model)

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Real-time optimization (RTO)

- Up to now we focused on control system performance and design for load and set-point changes.
- RTO is an approach that concerns with how the set points are specified.
- In real-time optimization, *a computer is used to optimize set points for control loops*.
- E.g. optimal temperature profile in a polymerization reactor to obtain polymer with desired product quality in minimum time (profile can change and need to readjusted if disturbance occur during batch)
- RTO uses process model and optimization algorithms to design optimal operating conditions

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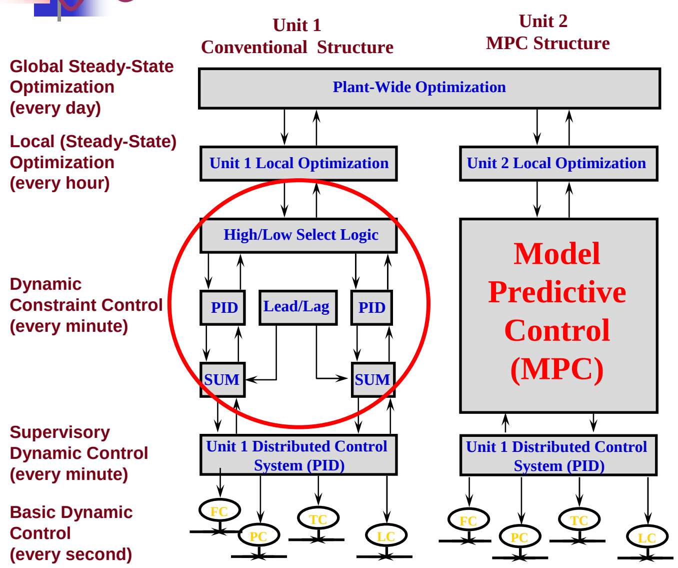
Control hierarchy in advanced plant-wide control



Role of MPC:

- Make fine adjustment for operating conditions of local units
- Take each local unit to the optimal condition fast but smoothly without violating constraints

Sample exam question

- Using block diagram algebra show that the block diagram with the Smith predictor on slide 5 is equivalent to the block diagram on slide 7.

Summary

- Advanced control strategies in chemical industries tend to be rather to rule than an exception
- APC (advance process control) has the ability to significantly improve control performance
- Smith predictor (eliminates the undesired effects of time-delays)
- IMC – a genric framework for model based feedback control design. Provides simple and more robust design than ZN for PID controllers (only one parameter to be tuned)
- State-of-the-art control approaches (MPC, RTO) use mode prediction and optimization algorithms to achieve the highest benefits from control