University of
South-Eastern Norway

Solution to exam in PEF3006 Process Control

Exam date: 4th December 2019. Duration: 4 hours. Weight in final grade of the course: 100%. Aids: None.

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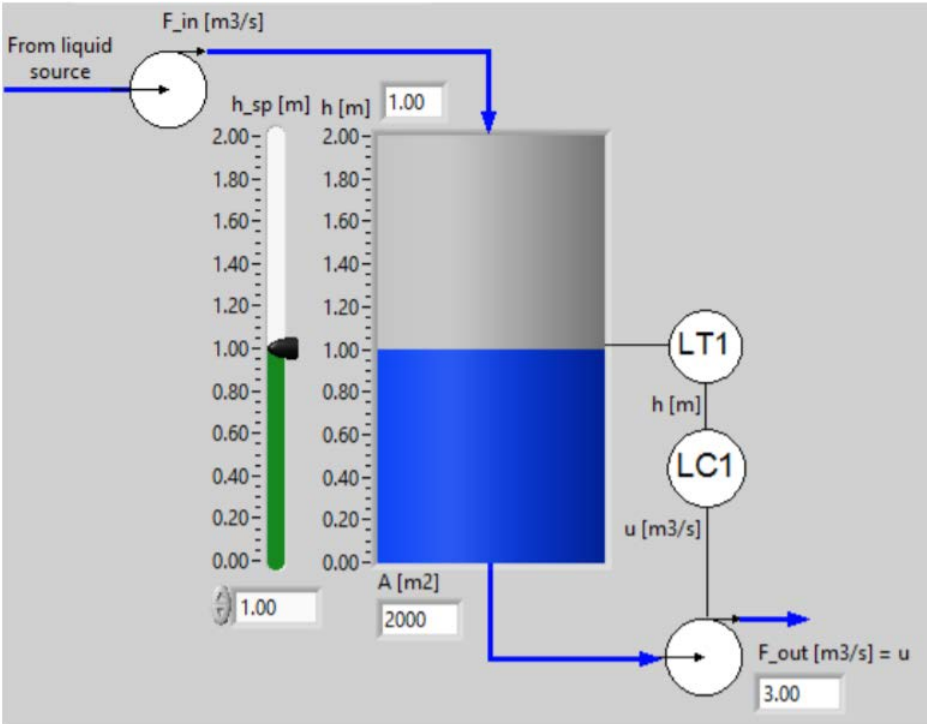
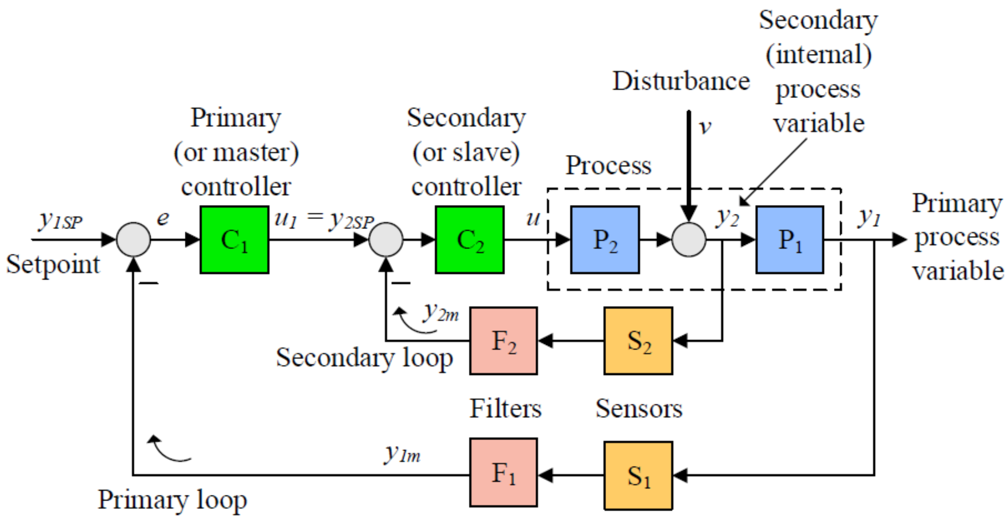
Solution to Problem 1 (10%)

The figure below shows a Piping and Instrumentation Diagram of a control system for the averaging level control of a tank. The inflow is assumed changing. There are two main requirements of the control system: (1) The outflow should be as smooth as possible. (2) The level of the tank should not exceed a given high limit nor a given low limit. Requirement 1 indicates that the level controller (LC1) is tuned for as soft (or smooth, or slow) control as possible. Requirement 2 indicates that the controller is *not too slow*, otherwise the level may exceed the limits at e.g. an approximate step change in the inflow (or a change in its mean or bias). The Skogestad method for PI setting is very suitable for tuning the level controller (however, details of the controller setting are not presented here).



Solution to Problem 2 (10%)

The figure below shows a general block diagram of a cascade control system. The control signal calculated by the primary controller is used as the setpoint of the secondary controller. The secondary control loop compensates quickly for the disturbance so that the disturbance does not influence the primary process output variable, and to this end, it is necessary that sensor S2 measures an internal process variable which is influenced by the disturbance. The main benefit of cascade control comparing with single loop control is the ability to more quickly and effectively compensate for process distrurbances.



Solution to Problem 3 (10%)

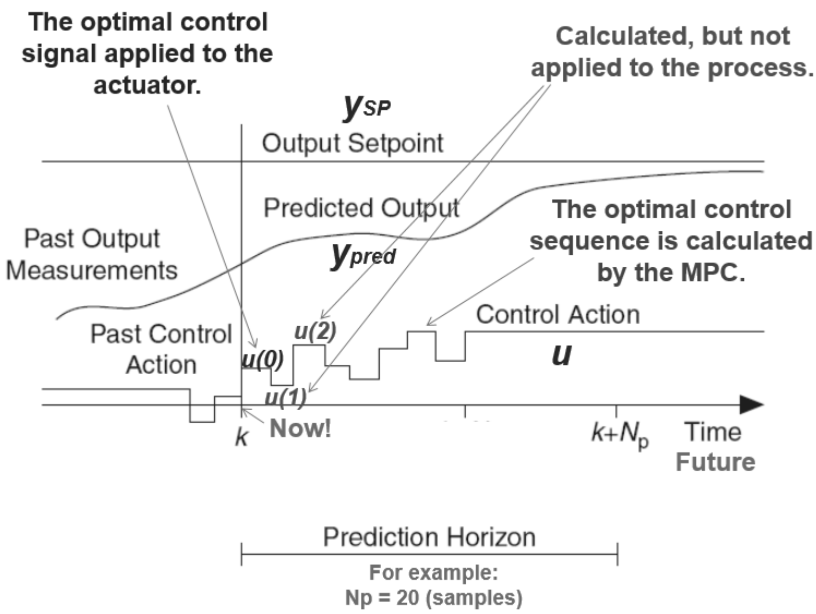
The MPC is a model-based controller that, continuously predicts the optimal future control sequence using the following information:

- An optimization criterion that typically consists of a sum of future (predicted) squared control errors and quadratic control signal changes.
- A process model
- The current process state obtained from measurements and/or state estimates from a state estimator which typically is in the form of a Kalman filter.
- Current, and, if available, future setpoint values and process disturbance values.
- Constraints (max and min values) of the control signal and the process variable.

From the optimal future control sequence, the first element is picked out and applied as control signal to the process. The above calculations are repeated at the next point of time (i.e. "continuously").

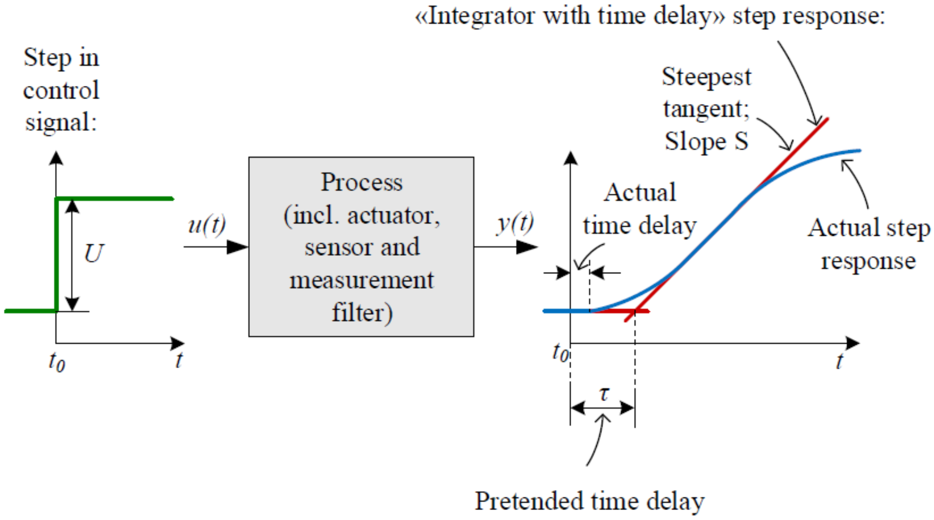
Some versions of the MPC assume linear process models, while others are based on nonlinear process models. The models may be multivariable and contain time delays.

Figure below illustrates the behaviour of the MPC.



Solution to Problem 4 (5%)

Run an experiment to get the process (open loop) step response:



Calculate normalized slope (or integrator gain):

$$K_i = \frac{S}{U}$$

PI settings:

$$K_p = \frac{1}{2K_i\tau}$$

$$T_i = 4\tau$$

Solution to Problem 5 (5%)

The controller should have direct action. Reason: Assume a positive change of the control signal to the valve, which then opens more. This cause the level to decrease; hence, the process gain is negative, which requires a negative controller gain, which per definition is direct action.

Solution to Problem 6 (5%)

Original Ziegler-Nichols settings: Kp = 0.45*10 = 4.5. Ti = 12/1,2 = 10 s.

Relaxed Ziegler-Nichols settings: Kp = 0.25*10 = 2.5. Ti = 1.25*12 = 15 s.

Solution to Problem 7 (5%)

At discrete time k:

$$T_f*dy_k/dt = u_k – y_k$$

Approximation of dy_k/dt with backward difference (Euler backward method):

$$dy_k/dt = (y_k – y_{k-1})/T_s$$

Inserting this in the differential equation above, gives:

$$T_f*(y_k – y_{k-1})/T_s = u_k – y_k$$

Solving for y_k gives:

$$y_k = (1 - a)*y_{k-1} + a*u_k$$

where

$$a = T_s/(T_f + T_s)$$

Solution to Problem 8 (5%)

Taking the Laplace transform:

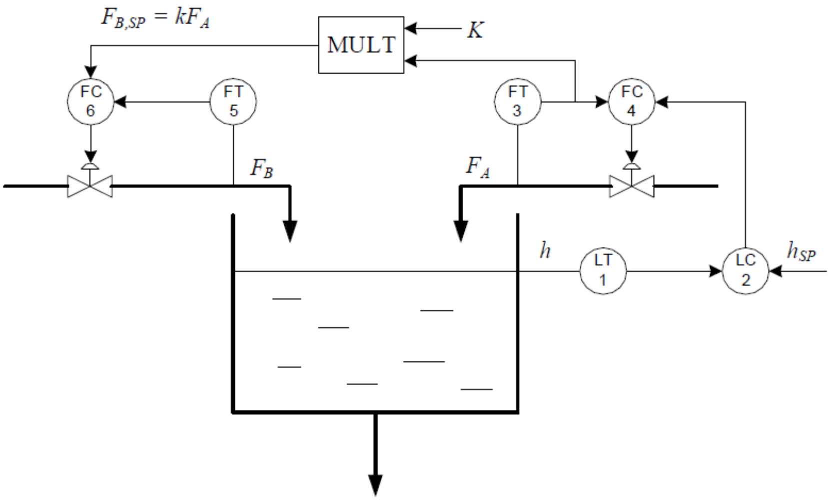
$$T_f*s*y(s) = u(s) – y(s)$$

which gives the following transfer function from u to y:

$$y(s)/u(s) = 1/(T_f*s + 1)$$

Solution to Problem 9 (5%)

See the figure below.



Solution to Problem 10 (10%)

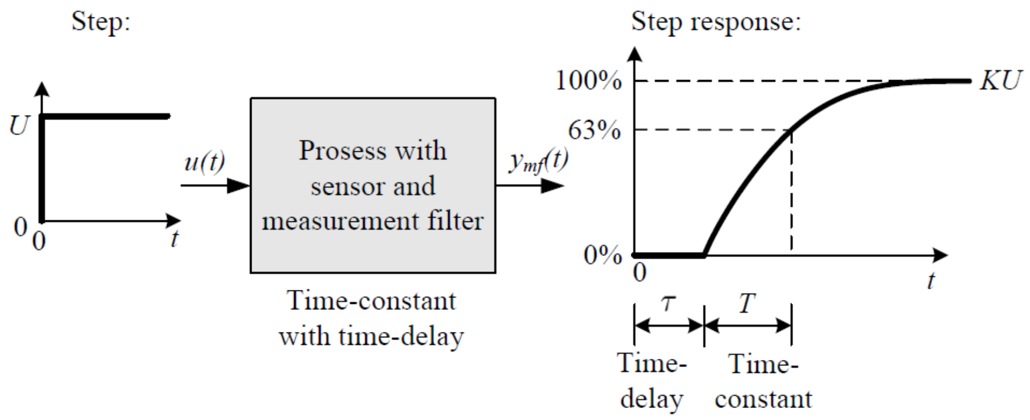
(10%) The feedforward controller can be derived by substituting θ by its setpoint, θ_{SP}, in the model, Eq. (1), and then solving for the control signal, u. According to the problem formulation, $\tau = 0$. The result is the following formula of the control signal, i.e. the feedforward controller:

$$u_f(t) = \left\{ c\rho V \dot{\theta}_{SP}(t) - c\rho F \left[\theta_{in}(t) - \theta_{SP}(t) \right] - U \left[\theta_e(t) - \theta_{SP}(t) \right] \right\} / K_h$$

The following variables – assuming they are not known by other means – must be measured to make the feedforward controller implementable: F (with a flow sensor), θ_{in} (temperature sensor), and θ_e (temperature sensor). The other quantities, i.e. c, ρ, V, U, and K_h are here assumed known.

Solution to Problem 11 (5%)

See the figure below (where "Process ..." is "system").



Solution to Problem 12 (5%)

Writing the differential form on the standard form T*dy/dt = Ku - y:

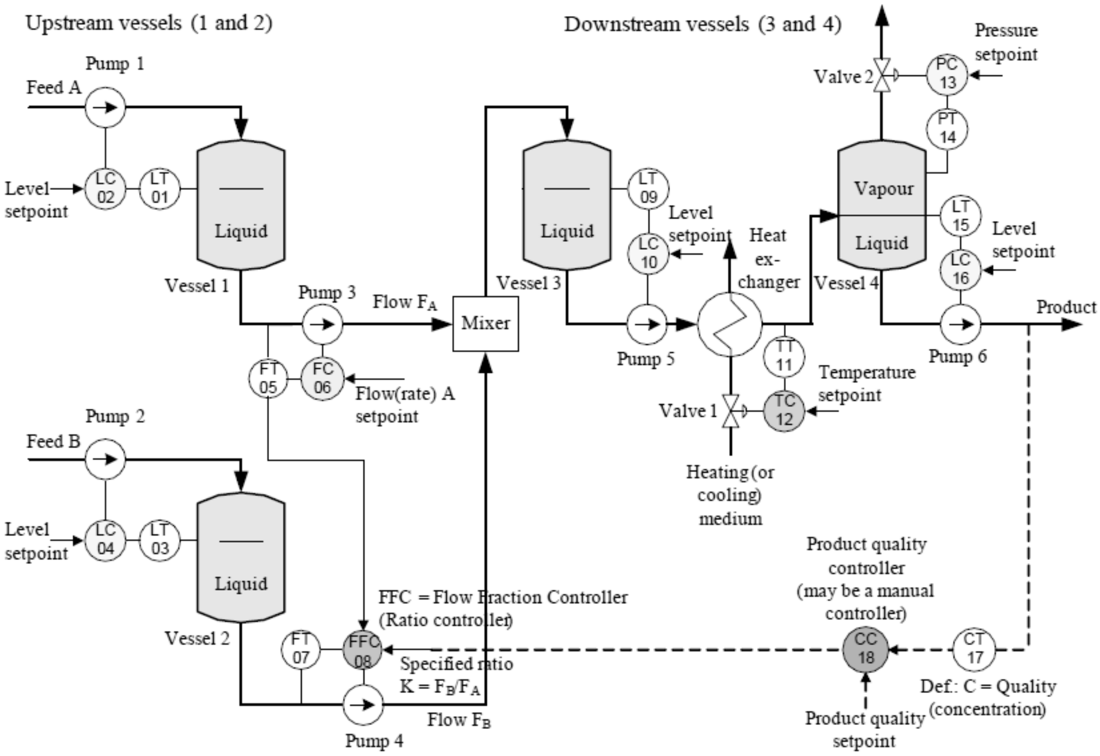
$$0.5*dy/dt = 2.5*u - y$$

which gives

$$K = 2.5 \text{ and } T = 0.5.$$

Solution to Problem 13 (20%)

The figure below shows one possible solution (the same as in the textbook). The dashed signal lines of the quality control loop assumed that an online production quality sensor is available (which, however, may not often be the case).


Upstream vessels (1 and 2)
Downstream vessels (3 and 4)
Pump 1
Feed A
Level setpoint
LC 02
LT 01
Liquid
Vessel 1
Pump 3
Flow F_A
Mixer
FT 05
FC 06
Flow(rate) A setpoint
Pump 2
Feed B
Level setpoint
LC 04
LT 03
Liquid
Vessel 2
FT 07
FFC 08
FFC = Flow Fraction Controller (Ratio controller)
Specified ratio $K = F_B/F_A$
Pump 4
Flow F_B
Liquid
Vessel 3
LT 09
LC 10
Level setpoint
Pump 5
Heat ex-changer
TT 11
TC 12
Temperature setpoint
Valve 1
Heating (or cooling) medium
Valve 2
PC 13
Pressure setpoint
PT 14
Vapour
Liquid
Vessel 4
LT 15
LC 16
Level setpoint
Pump 6
Product
Product quality controller (may be a manual controller)
CC 18
CT 17
Product quality setpoint
Def.: C = Quality (concentration)