

Multivariable Control

Laboratory experiment 2

The Quadruple Tank¹

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1. Introduction

The aim of this laboratory exercise is to study some different aspects of multivariable control systems. The ideas are illustrated on a quadruple-tank process with two inputs and two outputs. The process can be modified to have different dynamics: In one configuration the process is minimum phase, and in another configuration the process is nonminimum phase. In the lab we will study the pairing of different inputs and outputs, interaction between the control loops, decoupling, and fundamental limitations introduced by a nonminimum phase zero.

Preparations

Solve problems 1-3 in exercise session 7. Read this lab manual carefully as well as the lecture notes on fundamental limitations. At the beginning of the lab, you should also be able to discuss the points below:

Discussion points

1. Give real-world examples of systems where the step response initially goes in the wrong direction.
2. In which of the two possible process configurations is it easier to control the level of the lower tanks? Can you give an intuitive explanation?
3. Consider the configuration where most of the water enters the upper tanks. Increase the speed of one pump while decreasing the other. What short-term effects do you expect? What long-term effects do you expect?
4. Imagine a configuration where the flow from each pump is divided 50–50. Can you achieve different levels in the lower left and right tanks?

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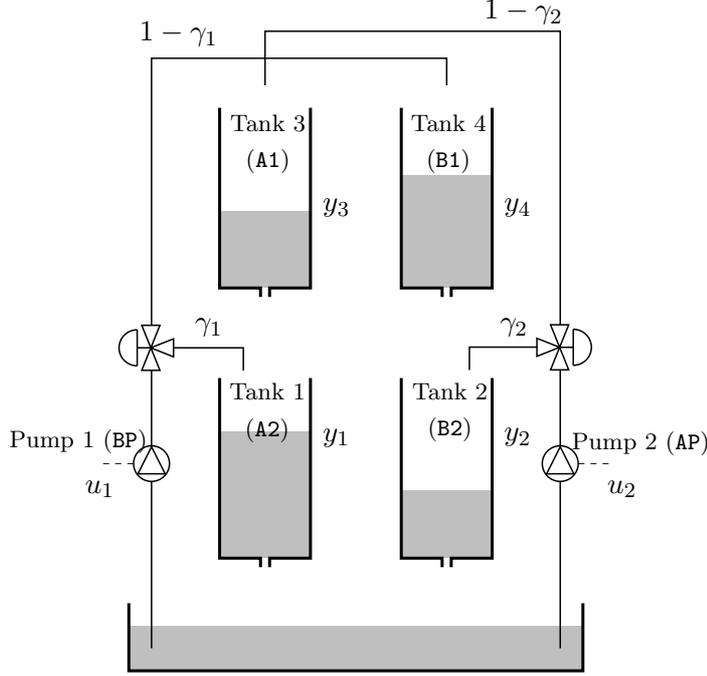


Figure 1 The quadruple-tank process.

2. The Process

The quadruple-tank process is shown in Figure 1. The goal is to control the water level in the lower tanks using the two pumps.

The control inputs u_1 , u_2 are the voltages (0–10 V) applied to the two pumps. The control outputs y_1 , y_2 are voltages (0–10 V) representing the levels in the lower tanks.

Nonlinear Model

In this section, a nonlinear model of the quadruple-tank process is derived. For each tank $i = 1 \dots 4$, mass balance and Bernoulli's law give that

$$A_i \frac{dh_i}{dt} = -a_i \sqrt{2gh_i} + q_{in_i}$$

where A_i [cm^2] is the cross-section of the tank, h_i [cm] is the water level, a_i [cm^2] is the cross-section of the outlet hole, g [cms^{-2}] is the acceleration of gravity, and q_{in_i} [cm^3s^{-1}] is the inflow to the tank.

Each pump $j = 1, 2$ gives a flow proportional to the control signal,

$$q_{pump_j} = k_j u_j$$

where k_j [$\text{cm}^3\text{V}^{-1}\text{s}^{-1}$] is a pump constant. The flows from the pumps are divided according to the two parameters $\gamma_1, \gamma_2 \in (0, 1)$. The flow to Tank 1 is $\gamma_1 k_1 u_1$ and the flow to Tank 4 is $(1 - \gamma_1) k_1 u_1$. Symmetrically, the flow to Tank 2 is $\gamma_2 k_2 u_2$ and the flow to Tank 3 is $(1 - \gamma_2) k_2 u_2$.

The measured level signals are $y_1 = k_c h_1$ and $y_2 = k_c h_2$, where k_c [Vcm^{-1}] is a measurement constant.

Considering the flow in and out of all tanks simultaneously, the dynamics of quadruple-tank process are given by

$$\begin{aligned}\frac{dh_1}{dt} &= -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}u_1 \\ \frac{dh_2}{dt} &= -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}u_2 \\ \frac{dh_3}{dt} &= -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}u_2 \\ \frac{dh_4}{dt} &= -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}u_1\end{aligned}$$

Stationary Points For a stationary operating point $(h_1^0, h_2^0, h_3^0, h_4^0, u_1^0, u_2^0)$, the equations above give that

$$\begin{aligned}\frac{a_3}{A_3}\sqrt{2gh_3^0} &= \frac{(1-\gamma_2)k_2}{A_3}u_2^0 \\ \frac{a_4}{A_4}\sqrt{2gh_4^0} &= \frac{(1-\gamma_1)k_1}{A_4}u_1^0\end{aligned}\tag{1}$$

and thus

$$\begin{aligned}\frac{a_1}{A_1}\sqrt{2gh_1^0} &= \frac{(1-\gamma_2)k_2}{A_3}u_2^0 + \frac{\gamma_1 k_1}{A_1}u_1^0 \\ \frac{a_2}{A_2}\sqrt{2gh_2^0} &= \frac{(1-\gamma_1)k_1}{A_4}u_1^0 + \frac{\gamma_2 k_2}{A_2}u_2^0\end{aligned}\tag{2}$$

If we chose stationary levels in the lower tanks, h_1^0, h_2^0 , we can obtain the stationary control signals u_1^0, u_2^0 by solving the linear system of equations (2). The stationary levels in the upper tanks, h_3^0, h_4^0 , are then obtained from (1).

Linear Model

Let $\Delta u_i = u_i - u_i^0$, $\Delta h_i = h_i - h_i^0$, and $\Delta y_i = y_i - y_i^0$. Introducing

$$u = \begin{pmatrix} \Delta u_1 \\ \Delta u_2 \end{pmatrix}, \quad x = \begin{pmatrix} \Delta h_1 \\ \Delta h_2 \\ \Delta h_3 \\ \Delta h_4 \end{pmatrix}, \quad y = \begin{pmatrix} \Delta y_1 \\ \Delta y_2 \end{pmatrix}$$

and linearizing around a stationary point gives the linear system

$$\begin{aligned}\frac{dx}{dt} &= \begin{pmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1 T_3} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2 T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{pmatrix} x + \begin{pmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{pmatrix} u, \\ y &= \begin{pmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{pmatrix} x,\end{aligned}$$

where

$$T_i = \frac{A_i}{a_i} \sqrt{\frac{2h_i^0}{g}}$$

The transfer matrix from u to y is given by

$$G(s) = \begin{pmatrix} \frac{\gamma_1 c_1}{1 + sT_1} & \frac{(1 - \gamma_2)c_1}{(1 + sT_1)(1 + sT_3)} \\ \frac{(1 - \gamma_1)c_2}{(1 + sT_2)(1 + sT_4)} & \frac{\gamma_2 c_2}{1 + sT_2} \end{pmatrix}$$

where $c_1 = T_1 k_1 k_c / A_1$ and $c_2 = T_2 k_2 k_c / A_2$.

Multivariable Zeros

As shown in the preparatory exercises, the zeros of $G(s)$ are given by the equation

$$(1 + sT_3)(1 + sT_4) - \frac{(1 - \gamma_1)(1 - \gamma_2)}{\gamma_1 \gamma_2} = 0$$

The system is found to be minimum phase (i.e., both zeros are stable) if $1 \leq \gamma_1 + \gamma_2 \leq 2$ and nonminimum phase (i.e., at least one zero is unstable) if $0 < \gamma_1 + \gamma_2 \leq 1$.

Relative Gain Array

The relative gain array (RGA) is a useful tool for determining what outputs should be controlled by what inputs for decentralized controllers.

As shown in the preparatory exercises, the RGA of $G(0)$ is given by

$$\begin{pmatrix} \lambda & 1 - \lambda \\ 1 - \lambda & \lambda \end{pmatrix}$$

where $\lambda = \gamma_1 \gamma_2 / (\gamma_1 + \gamma_2 - 1)$.

Process Data

The quadruple tank has approximately the following physical constants:

$$\begin{aligned} A_i &= 4.9 \text{ cm}^2 \\ a_i &= 0.03 \text{ cm}^2 \\ k_i &= 1.6 \text{ cm}^3/\text{V} \\ k_c &= 0.5 \text{ V/cm} \\ g &= 981 \text{ cm/s}^2 \end{aligned}$$

The flow from each pump is divided such that roughly 70 % goes through one tube extension and 30 % through the other. In the minimum phase case, the 70 % extensions are connected to the lower tanks and we have $\gamma_1 = \gamma_2 = 0.7$. In the nonminimum phase case, the 30 % extensions are connected to the lower tanks and we have $\gamma_1 = \gamma_2 = 0.3$.

The operating point in the lower tanks are chosen as $h_1^0 = h_2^0 = 10 \text{ cm}$. In the minimum phase case the stationary levels in the upper tanks are calculated to be $h_3^0 = h_4^0 = 0.9 \text{ cm}$ and in the nonminimum phase the stationary levels are $h_3^0 = h_4^0 = 4.9 \text{ cm}$. In both cases, the stationary control signals are $u_1^0 = u_2^0 = 2.6 \text{ V}$.

3. The Lab Interface

The controllers are designed and tested in MATLAB/Simulink. There is one Simulink model for simulation `quadtank_simulated` and another one for experiments on the real process `quadtank_real`. There is also a model for manually driving the physical process `quadtank_real_manual`.

The Simulink model for the simulated process is shown in Figure 2. The *Quad-tank* block contains the non-linear model of the quadruple tank process. Clicking on the block allows you to specify γ_1 and γ_2 for the process.

Before a simulation, you must define the two controllers C1 and C2 in the workspace. In the lab, the controllers will be of either PI or PID type. The controllers are conveniently designed using the commands `designpi` and `designpid` (use `help` on them!).

Run the script `define_process` to define the two systems `Gmin` and `Gnonmin` representing the linear process in the minimum phase and nonminimum phase case respectively.

It is also possible to specify two decoupling matrices `W1` and `W2` (see Section 5.3). The default choice is $W_1 = W_2 = I$ (the identity matrix), i.e. no decoupling.

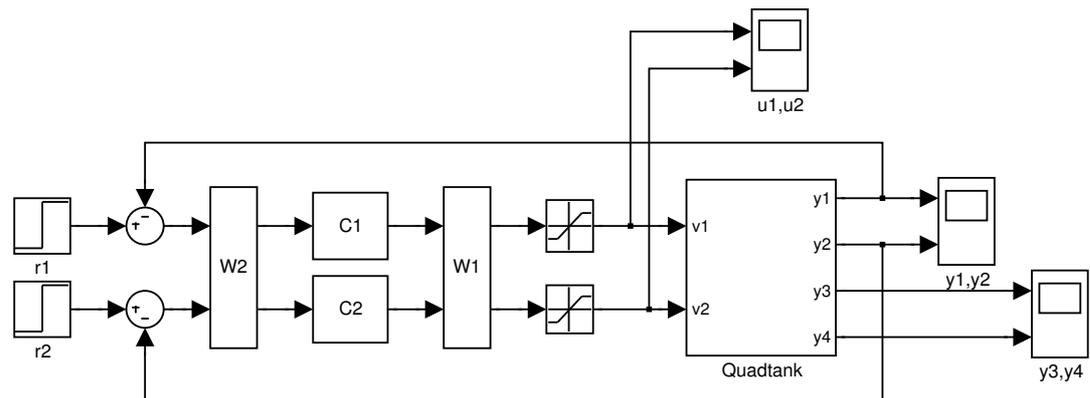


Figure 2 Simulink model `quadtank_simulated`.

4. Control in the Minimum Phase Case

We will start by controlling the process in the minimum phase case, where most water goes directly into the lower tanks. For simulations, make sure to enter the correct γ -values into the mask of the *Quadtank* block. For experiments on the physical process, make sure that the tubes of the process are connected so that 70 % of the flow from Pump 1 goes into Tank 1, and that 70 % of the flow from Pump 2 goes into Tank 2. This is achieved with the following valve configuration: AV1, AV2 and BV1 should be pulled out while BV2 should be pushed in (from the users perspective). Also make sure valves AV3, AV4, BV3, BV4 and V5 are all pushed down.

The γ -values given in this manual are from nominal construction data and values of individual processes do differ. If you experience differences between simulations and real process experiments, this might be a possible cause. The following steps suggest an experiment for identifying γ_1 and γ_2 .

1. Push up AV3, AV4, BV3, BV4 and down V5 to close all tank outlets. Use either of the two following configurations to choose operating mode (minimum or nonminimum phase).
 - (a) AV1, AV2 and BV1 pulled out, BV2. pushed in
 - (b) AV1, BV1 and BV2 pulled out, AV2 pushed in.
2. Open `quadtank_real_manual` and start a simulation
3. Use the slider gains to fill the the tanks so that the ones that fill fast reach ≈ 160 mm.
4. Measure the water levels $A1$, $A2$. $B1$ and $B2$.
5. Use

$$\gamma_1 = \frac{A2}{A2 + B1}, \quad \gamma_2 = \frac{B2}{B2 + A1}$$

After this is done, do the following, in order to use your identified values.

- Edit `define_process` and enter your measured values for `gamma1` and `gamma2` under either `% Minimum phase case` or `%Nonminimum phase case`.
- Enter your values in the mask of the Quadtank block of `quadtank_simulated`
- Rerun `define_process` and the synthesis script for C1 and C2.

4.1 Choice of Control Structure and Design

Exercise 1 Have a look at the transfer matrix G_{min} in MATLAB and also compute the zeros of the system:

```
>> Gmin
>> zero(minreal(ss(Gmin)))
```

Also compute the RGA of $G_{min}(0)$:

```
>> G0 = evalfr(Gmin,0*i)
>> G0.*transpose(inv(G0))
```

Do the results agree with the preparatory exercises? ◇

Now compute the RGA matrix for higher frequencies, say $\omega = 0.1, 0.5, 1, 10, 100$ rad/s, that is, we control the closed loop system faster and faster. How does the RGA matrix change with increasing frequency?

The RGA analysis suggests that we should control Tank 1 with Pump 1 and Tank 2 with Pump 2. If we ignore the cross-terms in the transfer matrix, we see that the problem is reduced to controlling the two single-tank processes

$$G_{min11}(s) = \frac{\gamma_1 c_1}{1 + sT_1}, \quad G_{min22}(s) = \frac{\gamma_2 c_2}{1 + sT_2}$$

From the basic course we know that we can control a single-tank process without stationary error using a PI controller. The resulting control structure is shown in Figure 3.

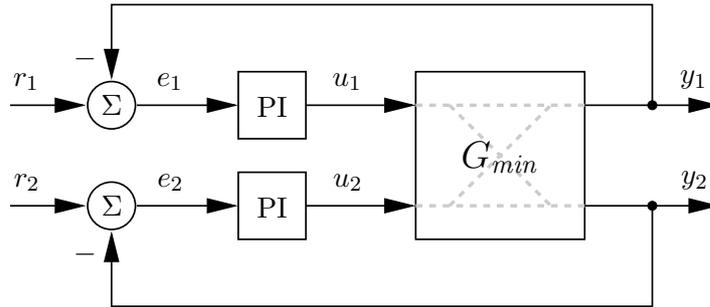


Figure 3 The control structure in the minimum phase case.

We will use pole-placement to design the PI controllers in the two loops. The desired characteristic polynomial of each closed loop is specified as

$$s^2 + 2\zeta\omega s + \omega^2$$

4.2 Experiments

Exercise 2 Make sure that the Simulink models agree with the control structure described above. Double-click on the process block in Simulink to set the value of γ_1 and γ_2 . Use the command `designpi` to design the two PI controllers `C1` and `C2` for the subsystems G_{min11} and G_{min22} . Use $\zeta = 0.7$ and experiment with different ω . Try the controller in simulations, and, when it works well, also on the real process.

Set the step time of step block `R1` to 50 and `R2` to 100 and the simulation stop time (found in the Simulation menu under Configuration Parameters) to 150. If you have difficulties to find a controller which settles within these times, you may increase them. However, have in mind that this implies longer experiment durations.

If you try large values of ω , say $\omega > 0.5$, you may see large overshoots in the water levels and in some cases even combinations of over- and undershooting. Explain this behaviour! How can you eliminate this undesired phenomena? *Hint:* Study the plot of the control signals.

Can you notice any cross-coupling in the system response? How fast can you make the system? What limits the achievable performance? \diamond

5. Control in the Nonminimum Phase Case

We will now try to control the process in the nonminimum phase case, where most water goes to the upper tanks. You **must** move the tubes in the physical process such that 70 % of the flow from Pump 1 goes into Tank 4, and that 70 % of the flow from Pump 2 goes into Tank 3. This is achieved with the following valve configuration: `AV1`, `BV1` and `BV2` should be pulled out while `AV2` should be pushed in (from the users perspective).

5.1 Choice of Control Structure and Design

Exercise 3 Take a look at the transfer matrix G_{nonmin} in MATLAB. Compute the zeros of the system. Are they stable? Also compute the RGA of $G_{nonmin}(0)$ and $G_{nonmin}(0.02i)$. Do the results agree with the preparatory exercises? \diamond

The RGA analysis suggests that we should control Tank 1 with Pump 2 and Tank 2 with Pump 1. If we ignore the cross-terms in the transfer matrix, the problem is reduced to controlling the two double-tank processes

$$G_{nonmin12} = \frac{(1 - \gamma_2)c_1}{(1 + sT_1)(1 + sT_3)}, \quad G_{nonmin21} = \frac{(1 - \gamma_1)c_2}{(1 + sT_2)(1 + sT_4)}$$

From the basic course we know that we can control a double-tank process without stationary error using a PID controller. The resulting control structure is shown in Figure 4.

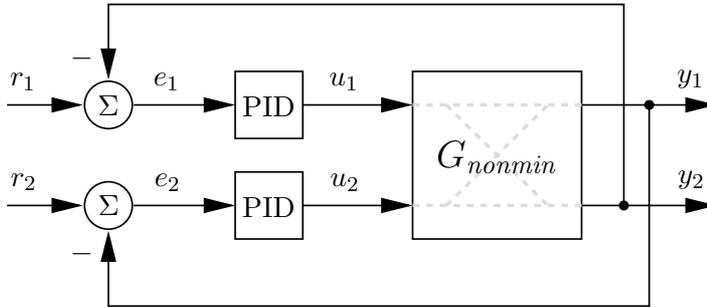


Figure 4 The control structure in the nonminimum phase case.

Again, we will use pole placement to design the PID controllers in the two loops. The desired characteristic polynomial of each closed loop is specified as

$$(s + \alpha\omega)(s^2 + 2\zeta\omega s + \omega^2)$$

5.2 Experiments

Exercise 4 You **must** modify the Simulink models so that they agree with the new control structure as seen in Figure 4. Don't forget to change the values of γ_1 and γ_2 in the simulated process block as well.

Set the step time of step block R1 to 100 and R2 to 200 and the simulation stop time to 300. If you have difficulties to find a controller which settles within these times, you may increase them. However, have in mind that this implies longer experiment durations.

Use the command `designpid` to design the two PID controllers C1 and C2. Use $\zeta = 0.7$, $\alpha = 1$, and experiment with different values of ω . Try the controller in simulations, and, when it seems to work well, also on the real process. How should W1 look like according to the RGA reasoning?

Can you see the nonminimum phase behavior of the system in the step responses? How fast can you make the system? What limits the achievable performance? (*Warning:* The process is much slower and more difficult to control in this setting. A step response can take several minutes!)

5.3 Decoupling

It is often possible to reduce the cross-coupling in a multivariable system by a suitable change of coordinates. The idea is to introduce new variables $\tilde{y} = W_2 y$ and $\tilde{u} = W_1^{-1} u$ such that the new system

$$\tilde{G}(s) = W_2 G(s) W_1$$

becomes as diagonal as possible. It is then possible to design a decentralized controller

$$\tilde{u} = \begin{pmatrix} C_1 & 0 \\ 0 & C_2 \end{pmatrix} \tilde{e}$$

for the decoupled system. The control structure is shown in Figure 5.

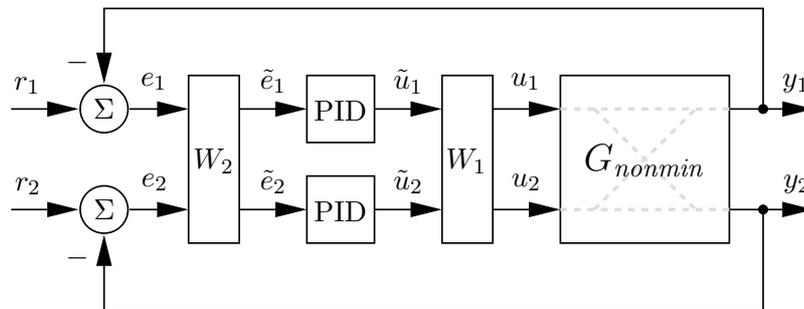


Figure 5 Decoupling in the nonminimum phase case.

In our case, since the process is symmetric ($G_{11} = G_{22}$ and $G_{12} = G_{21}$), choosing

$$W_1 = W_2 = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

will result in a complete diagonalization of the system. (Choosing W_1 and W_2 may be non-trivial in the general case). Notice that \tilde{y}_1 corresponds to the sum of the lower tank levels, while \tilde{y}_2 corresponds to the difference of the lower tank levels.

Exercise 5 Enter the matrices W_1 and W_2 in MATLAB and then compute the transformed system \tilde{G} :

```
>> Gtilde = minreal(W2*Gnonmin*W1)
```

Notice that the the minimum phase dynamics are collected in \tilde{G}_{11} , while the nonminimum phase dynamics are collected in \tilde{G}_{22} . It should thus be harder to control \tilde{y}_2 than \tilde{y}_1 . Does this agree with your intuition?

Exercise 6 Design two PID controllers for the systems \tilde{G}_{11} and \tilde{G}_{22} . It is probably possible to achieve higher bandwidth in the first loop than the second one (why?).

Try the controller in simulations and also on the real process. Do you get better responses than you did in Exercise 4?