

Control Theory and Practice
Advanced Course

Laboratory experiment:
THE FOUR-TANK PROCESS

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1 Introduction

In this laboratory experiment we will control the four-tank process, which is a multivariable system. In particular we will investigate interactions between inputs and outputs as well as properties of non-minimum phase dynamics.

The experiment is divided into two occasions. On the first occasion, the modeling and the manual control is performed. This will give you numerical values of some important parameters. Relevant parts of the computer exercises are then repeated, using the identified parameters, to obtain model based controllers. On the second occasion, the control design is evaluated.

Signing up for the laboratory experiment: You should form groups of four students, and then sign up for the laboratory through BILDA. It is important that you sign up for the same four-tank process (A , B , C , D) on both laboratory occasions, since you will use the model obtained on the first occasion for the control design in the second occasion.

Preparations for occasion 1: Chapters 3.3, 3.5, 3.6, 6.5, 7.3-7.5, 7.7, 8.3, 10.5 in Glad, T. and Ljung, L.: “Control theory—multivariable and nonlinear methods”. Read the lab instructions and solve the problems that can be solved in advance. Also read the Appendix. **Note: You need to be registered for the course in order to log on to the computers.**

Preparations for occasion 2: Four controllers should be prepared and brought to occasion 2. The controllers can be generated through repeating relevant parts of the computer exercises using the parameters identified during lab occasion 1.

One controller for the minimum phase case and one for the non-minimum phase case. In addition to this, construct a robustified controller (for each cases) using the Glover-McFarlane method. Bring the MATLAB scripts and generate the controllers on the lab computer. On page 8 it is described how to name and save the controllers.

Presentation: All problems in this exercise should be solved and be presented in a written report. The date when the report should be handed in is indicated on the course website. The report should be a full report, contain *abstract* and *conclusions*, relevant figures and tables with *captions* and *legends*, etc. Focus on explaining what you have done, and do not repeat theorems but cite them. Remember to write concise (a report is not a novel), be specific in your writing (“the overshoot is 20%” compared to “the overshoot is not so good”), and check your spelling. The report will be graded based on both the content and presentation.

Additional information: Check the course website and the white-board in the lab for additional instructions. Don’t forget to save your data to plot the figures for the report.

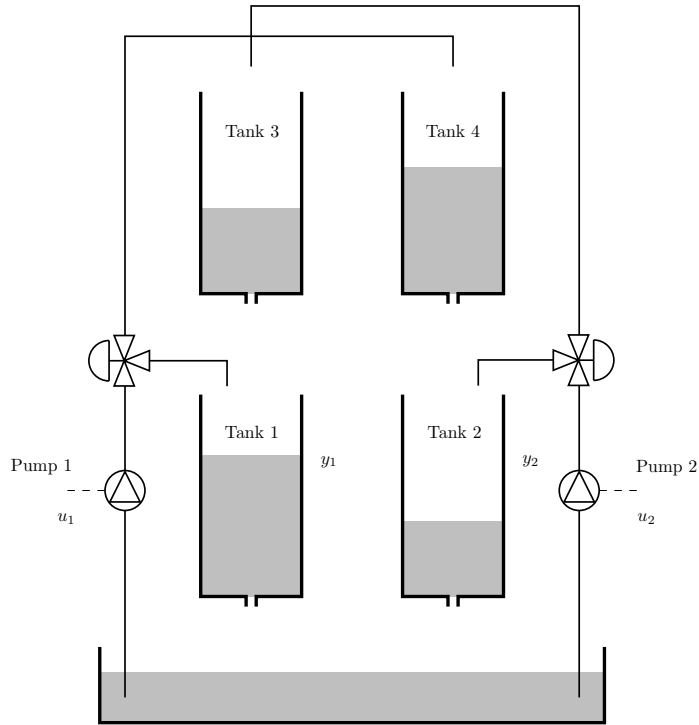


Figure 1: The four-tank process

2 Laboratory occasion 1

In the exercises below a physical model of the four-tank process will be constructed. Then, we will investigate manual control and coupling between the tanks. Performance limitations due to non-minimum dynamics will be investigated. Finally, we will design model based controllers, more specifically decentralized PI control and robust control using the Glover-McFarlane method.

2.1 Modeling

Here the nonlinear differential equations which describe the four-tank process will be derived. The process is shown schematically in Figure 1. For each tank the following relation holds:

$$dV = (q_{in} - q_{out})dt$$

where dV is the change in water volume during the time dt . Divide this equation by dt and assume that $V = Ah$ where A is the cross section area of the tank and h its water level. Then we obtain

$$A \frac{dh}{dt} = q_{in} - q_{out}$$

For the outflow of water, Bernoulli's law holds:

$$q_{out} = a\sqrt{2gh}$$

where a is the cross section area of the outlet hole and $g = 981\text{cm/s}^2$. The flow q generated by a pump is considered proportional to the applied pump voltage u :

$$q = ku$$

where k is the constant. This flow is then divided according to

$$q_L = \gamma ku, \quad q_U = (1 - \gamma)ku, \quad \gamma \in [0, 1]$$

where γ indicates the setting of the valve which is connected to the pump. q_L denotes the flow to the lower tank and q_U is the flow to the upper tank.

Exercise 2.1.1. Show that the following equations describe the water levels in the four tanks.

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

where index i in A_i , a_i and h_i refer to tank i and index j in k_j and γ_j refer to pump j and valve j .

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Assume that the levels in the lower tanks are measured by sensors for which the output voltages y_i are proportional to the water levels h_i :

$$y_i = k_c h_i$$

where k_c is a constant.

Exercise 2.1.2. Write down the equations which describe an equilibrium $u_1^0, u_2^0, h_1^0, h_2^0, h_3^0, h_4^0, y_1^0, y_2^0$ for the tanks.

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Let $\Delta u_i = u_i - u_i^0$, $\Delta h_i = h_i - h_i^0$ and $\Delta y_i = y_i - y_i^0$ denote the deviations from an equilibrium. Introduce

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

Exercise 2.1.3. Show that the linearized system is given by

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

$$y = \begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix} x$$

where

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

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Exercise 2.1.4. Show that the transfer matrix from u to y is given by

$$G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} = \begin{bmatrix} \frac{\gamma_1 k_1 c_1}{1+sT_1} & \frac{(1-\gamma_2)k_2 c_1}{(1+sT_3)(1+sT_1)} \\ \frac{(1-\gamma_1)k_1 c_2}{(1+sT_4)(1+sT_2)} & \frac{\gamma_2 k_2 c_2}{1+sT_2} \end{bmatrix}$$

where $c_i = T_i k_c / A_i$.

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Exercise 2.1.5. The zeros of $G(s)$ are given by the zeros of

$$\det G(s) = \frac{k_1 k_2 c_1 c_2}{\prod_{i=1}^4 (1+sT_i)} \left[(1+sT_3)(1+sT_4) - \frac{(1-\gamma_1)(1-\gamma_2)}{\gamma_1 \gamma_2} \right]$$

Show that $G(s)$ is minimum phase if $1 < \gamma_1 + \gamma_2 \leq 2$ and that $G(s)$ is non-minimum phase if $0 < \gamma_1 + \gamma_2 \leq 1$.

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Exercise 2.1.6. Show that the RGA of $G(0)$ is given by

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

where $\lambda = \gamma_1 \gamma_2 / (\gamma_1 + \gamma_2 - 1)$. In the minimum phase case we have $\gamma_1 = \gamma_2 = 0.625$ and in the non-minimum phase case we have $\gamma_1 = \gamma_2 = 1 - 0.625 = 0.375$. Calculate the RGA matrix for both these cases.

All tanks have cross section area $A = 15.52 \text{ cm}^2$. However, their effective outlet hole areas vary slightly, and therefore these have to be determined experimentally. We will use different outlet hole sizes in the upper tanks depending on if we are studying the minimum phase or non-minimum phase case. (The outlet holes in the two lower tanks should always have the same size). This means that we will have to determine six (effective) outlet hole areas altogether.

The level sensors have the proportionality constant $k_c = 0.2 \frac{\text{V}}{\text{cm}}$. For the minimum phase case, $\gamma_1 = \gamma_2 = 0.625$ and for the non-minimum phase case we have $\gamma_1 = \gamma_2 = 1 - 0.625 = 0.375$.

In order to determine the remaining parameters, $(a_1 \ a_2 \ a_{3,min} \ a_{3,nonmin} \ a_{4,min} \ a_{4,nonmin} \ k_1 \ k_2)$, experiments will be performed.

It is important to prepare proposals for suitable experiments (in order to solve the problems stated below) before performing the laboratory exercise.

Then, in order to perform the experiments, the four-tank process will be set up according to the following instructions:

1. Turn on the computer and login with your KTH-account¹.
2. Connect the minimum phase case according to the instructions in appendix A.2.
3. Double-click the icon “Quadrupletank” at the Desktop.
4. The program starts by asking if any controllers are to be loaded. Answer no by typing “n” and pressing enter.
5. Start the program by pressing the green Start button.
6. Turn on the two UPM’s by pushing the buttons at the back.
7. Choose 50 (% of maximum voltage) of the control signals in the boxes “Control sig. pump 1/2”, and check that water is pumped into all tanks.

Exercise 2.1.7. Propose a suitable experiment² to determine k_1 and $k_2 \left[\frac{\text{cm}^3}{\text{s}\cdot\text{V}}\right]$, and perform it.

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Hint: All measurement are given as percentage of their maximum value.

¹You need to be registered for the course to get access to the computers.

²Tip: there might be air in the tubes, even when the pumps are on. Let the water flow and squeeze the tubes carefully to eliminate the air. A good idea is to run the experiment with $u_1=u_2=7.5 \text{ V}$ (50% of maximum voltage).

Exercise 2.1.8. Propose a suitable experiment to determine the four effective outlet hole areas a_i for the minimum phase case, and perform it. (In order to save time, we will determine $a_{3,nonmin}$ and $a_{4,nonmin}$ later.)

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2.2 Manual control

Solve the problems below for both the minimum phase and the non-minimum phase case. It is suitable to start with minimum phase.

Exercise 2.2.1. Set the pumps on 50 (% of maximum voltage). Wait until stationarity and read the levels on all four tanks from the scale indicated in cm on the four-tank process. Are the levels (fairly) in accordance with the calculations on the equations in Exercise 2.1.2³?

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Exercise 2.2.2. Study the step responses (the two outputs) from one input at a time for the two cases (minimum and non-minimum phase). Does the system seem to be coupled? Is this in accordance with the indications of the RGA?

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Exercise 2.2.3. Choose suitable reference levels for the two lower tanks, for example 15 cm (60% of full tank). Try to manually set the pump voltages so that the values displayed on the computer screen become equal to the reference values⁴. How long is the transient time?

Hint: Patience is required for the non-minimum phase case. (If you have not succeeded after 10 minutes, skip it and move on.)

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³The level sensors are not calibrated exactly, and therefore the value you read from the scale does not correspond exactly to the value displayed on the screen.

⁴Because of sensitive technique of measurement, it might happen that the signals from the level sensors are subject to small jumps every now and then, so called “offset jumps”.

1. Connect the components according to the non-minimum phase case described in appendix A.2.
2. Go back to Exercise 2.1.8 and determine $a_{3,nonmin}$ and $a_{4,nonmin}$.
3. Now repeat the exercises above for the non-minimum phase case.

Exercise 2.2.4. For the above exercises, what are the most important differences between the minimum phase and the non-minimum phase case?

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The first laboratory occasion is now completed, but don't forget to:

1. Log out from the computer, and turn off the UPM:s.
2. Make sure that the laboratory spot is nice and clean.
3. Do the preparation tasks for the next laboratory occasion (they are described in the next section.)

3 Calculation of controllers

Before laboratory occasion 2, four controllers will be calculated.

Exercise 3.1.1. The values of the effective outlet hole areas, the k_i and γ_i ($i = 1,2$) that you obtained will now be used to calculate controllers for the next laboratory occasion. Therefore, change the values in the files `minphase.m` and `nonminphase.m`. After that, repeat relevant parts of the computer exercises to obtain four controllers. Two controllers for the minimum phase case and two for the non-minimum phase case. In each phase-case, the first controller should be the decentralized controller which you thought was the best when performing the computer exercise. Do not forget to motivate your choice. The second controller should be a robustified Glover-McFarlane controller.

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The controllers are saved as `.MAT` files using the function `save` (type `help save` for more information). The files must be named `reg1.MAT`, `reg2.MAT`, `reg3.MAT` and `reg4.MAT` and must contain state space representations of controllers. The state space matrices must be named A , B_y , C and D_y .

Note: It is preferred, and a huge advantage, to bring a MATLAB script file that generates the controllers in the lab. There are some incompatibilities between different MATLAB versions, and it also lets you recompute the parameters at the second occasion if the four tank process has changed.

If the controller F is available on transfer function form, the following MATLAB code can be used to save it:

```
F=ss(F,'min');  
[A,By,C,Dy]=ssdata(F);  
save regX.MAT A By C Dy
```

4 Laboratory occasion 2

4.1 Decentralized control

The exercises below require that you have repeated the design process in the computer exercises with the parameters obtained on the previous lab occasion. Make sure that small step responses and load disturbances do not cause saturation of the control signals. Start by setting up the four-tank process in the following way:

1. Use the same laboratory equipment as in laboratory occasion 1 to connect the four-tank process.
2. Turn on the computer and login with your KTH-account⁵.
3. Connect the minimum phase case according to the instructions in appendix A.2.
4. Generate and save the four controllers (according to the instructions in section 3).
5. Double-click the icon “Quadrupletank” on the Desktop.
6. The program starts by asking if you want to load controllers. Answer yes by typing “y” and then press enter. Locate and select `reg1.MAT` (the remaining controllers will then load automatically).
7. Start the program by pushing the green Start button.
8. Turn on both UPM:s by pushing the button at the back.
9. Choose 50 (% of maximum voltage) of the control signals in the boxes “Control sig. pump 1/2”, and check that water is being pumped into all tanks.

Solve the exercises below for both the minimum phase and non-minimum phase case. It is suitable to start with the minimum phase case.

Exercise 4.1.1. Wait until stationarity. Choose the best decentralized PI controller. Choose Automatic in the popup menu “Operational Mode”. Make sure that you work with small deviations from these levels, about 5 percentage points. Investigate the system’s response from a step in one of the reference signals. What is the rise time and the overshoot? Also, investigate the system’s response to different load disturbances: pour a cup of water in one of the lower tanks; open an extra outlet in one of the upper tanks. How long time does it take for the controller to eliminate the load disturbances?

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⁵You need to be registered for the course to get access to the computers.

Now connect the non-minimum phase case according to the instructions in appendix A.2. Then repeat the exercise above for the non-minimum phase case. (Problems can occur when opening an extra outlet in one of the upper tanks. In that case, specify what kind of problems that you get.)

Exercise 4.1.2. For the exercises above, what are the most important differences between the minimum phase and non-minimum phase case?

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4.2 Robust control

The exercises below require that you have repeated the design procedures in computer exercise 4 using the parameters obtained previously in this laboratory experiment.

Solve the problems below for both the minimum phase and the non-minimum phase case. It is suitable to start with the latter, since the laboratory equipment now is connected according to the non-minimum phase case.

Exercise 4.2.1. Wait until stationarity. Choose the Glover-McFarlane controller calculated according to the instructions in computer exercise 4. Choose Automatic in the pop up menu “Operational Mode”. Make sure that you work with small deviations from these levels. Investigate the system’s response to a step in one of the reference signals. What is the rise time and the overshoot? Also, investigate responses from different load disturbances: pour a cup of water in one of the lower tanks; open an extra outlet in one of the upper tanks. How long time does it take for the controller to eliminate the load disturbances?

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Exercise 4.2.2. What are the most important differences in performance when comparing the different controllers?

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Connect the minimum phase case according to the instructions in appendix A.2. Then repeat the exercises above for the minimum phase case.

Exercise 4.2.3. For the above exercises, what are the most important differences between the minimum phase and the non-minimum phase case?

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The second laboratory occasion is now completed, but don't forget to:

1. Log out from the computer, and turn off the UPM:s.
2. Make sure that the laboratory spot is nice and clean.
3. Write the report!

A Manual for the four-tank process

This manual is divided into four parts. The first part describes how to connect the process. The second describes how to connect the minimum phase and non-minimum phase case. The third part deals with the graphic user interface. The fourth part deals with disconnecting the process.

Note: You will need to perform the steps in appendix A.2.

A.1 How to connect the components of the four-tank process

The four-tank process consists of two double-tank processes connected to each other. The double-tanks are used for the laboratory experiments in the basic control course. Now we will describe how to connect the components of the four-tank process.

- Find the two double-tank processes that you are going to use. (Your group letter decides which two process that you are going to use, see “Signing up for the laboratory experiment” on page 1.) From now on, we will denote these two process “left” and “right”, as seen from the front. Carefully remove the blue water bowls. Release the right process by disconnecting the two cords connected to it. Carefully put the right process as close to the left process as possible. (Put both processes at the same table, so that there is no differences in altitude between them). On top of the cupboard at the back of the hall, there is a bigger water bowl which you will place under both the two lower tanks. Fill it with water, almost to the top.
- We will only use the computer of the left process, and we will soon connect the measurement and control signals. However, we will use the UPM:s (Universal Power Module) of both processes. There is an I/O card which belongs to the computer, and you find it at the back of the computer. We will use the card’s analogue Input and Output sockets. The left process should already be correctly connected, but to be sure we will verify it. Its control signal ⁶ should be connected to the card’s “Analog Output kanal 0”. Its level sensor for the lower tank⁷ should be connected to the card’s “Analog Input kanal 5”. The remaining three level sensor cords should not be connected. Disconnect the cords which are connected to the I/O card of the right computer (not the broad gray flat band cables). Move the UPM of the right process closer to the left one, so that its cords can be connected to the I/O card of the left computer. Connect the control signal of the right process to the card’s “Analog Output kanal 1” and the lower tank level sensor of the right process to “Analog input kanal 4”. Finally, connect the two non-connected cords ⁸ from the right UPM to the right process. If you are unsure: check once again that you have connected the process correctly!

⁶The black cord which is connected to “From D/A” at the UPM.

⁷The white socket, (marked with 2), at the broad socket with 4 channels which is connected to “To A/D” at the UPM.

⁸The black cord connected to “To Load” at the UPM and the gray cord.

A.2 Minimum phase and non-minimum phase settings

Depending on which phase case you are working with, you should use different outlet holes of the upper tanks, and connect the cords differently. Below you find a description of this procedure.

For each double-tank process, there are three extra outlet plugs (besides those that are already screwed under the tanks). One located far to the left which has no holes, one in the middle which has a small hole and finally one to the right which has a large hole.

In the minimum phase case, each pump pumps most of the water into “its own” lower tank, and only a smaller fraction of water into the upper tank at the other side. With this setting, we obtain a γ larger than 0.5. In the non-minimum phase case we have the opposite situation, and γ is therefore less than 0.5.

A.2.1 The minimum phase case is connected in the following way

- Put something on top of the two lower tanks, for example a paper towels. (To make sure that nothing falls down into them ⁹.)
- Use the wrench attached to the process to unscrew the plugs under both the upper tanks. Place each screw among the set of extra screws on each process (to the left of the plug located at the far right side).
- Put the small outlet holes in both the upper tanks. It is **not** necessary to pull tight. (Remember that the processes are fragile.)
- The four tubes, which will be connected according to the instructions below, have to end approximately 27 cm above the bottom of the upper tanks¹⁰. It is a good idea to pull the tubes through the holes located at the top of the four-tank process, so that the tubes go partly at the back of the process.
- Pull the tube from “Out 1” at the left process to the extra plastic pipe next to tank 3, so that its water falls directly into tank 1. (The numbering of the tanks is given in Figure 1 on page 2.)
- Pull the tube from “Out 2” at the left process to tank 4.
- Pull the tube from “Out 1” at the right process to the extra plastic pipe next to tank 4, so that its water falls directly down in tank 2.
- Pull the tube from “Out 2” at the right process to tank 3.

⁹If anything falls into the tanks, one has to disconnect tubes and cords from that process. Then one has to tilt the process very carefully so that the item that fell into the tank falls out.

¹⁰If the tubes end at different altitudes, the constants k_1 , k_2 , γ_1 and γ_2 can be affected, because the driving force acting on the water is changed.

A.2.2 The non-minimum phase setting is obtained in the following way

- Put something on top of the two lower tanks, for example a paper towels. (To make sure that nothing falls down into them).
- Unscrew the plugs located under the two upper tanks. For each process, place the plug among the set of extra screws (to the right of the plug located at the far left side).
- Put the medium size holes in the two upper tanks. It is **not** necessary to pull tight. (Remember that the processes are fragile.)
- The four tubes, which will be connected according to the instructions below, have to end approximately 27 cm above the bottom of the upper tanks. It is a good idea to pull the tubes through the holes located at the top of the four-tank process, so that the tubes go partly at the back of the process.
- Pull the tube from “Out 2” at the left process to the extra plastic pipe next to tank 3, so that its water flows directly into tank 1.
- Pull the tube from “Out 1” at the left process to tank 4.
- Pull the tube from “Out 2” at the right process to the extra plastic pipe next to tank 4, so that its water falls directly into tank 2.
- Pull the tube from “Out 1” at the right process to tank 3.

A.3 The graphic user interface

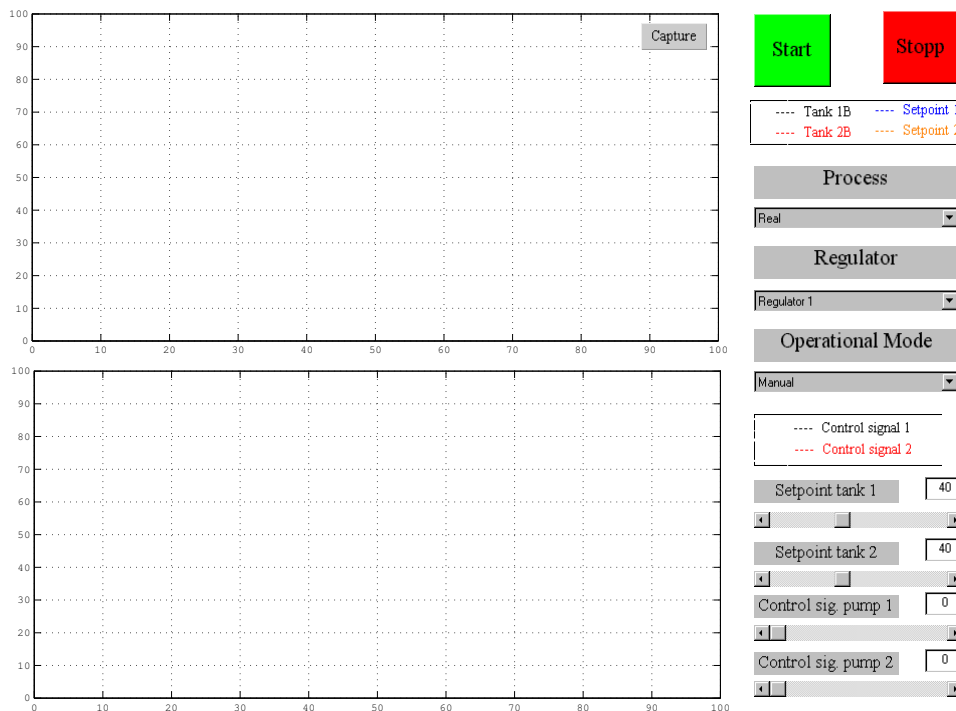


Figure 2: The graphic user interface.

- The interface is opened by double-clicking on the “Quadrupletank” MATLAB icon on the desktop.
- The program starts by asking if you want to load controllers. Choose yes or no depending on if you have designed controllers or not.
- Click on the green or red button at the top to the right to start or stop the process.
- Click on the popup menu **Regulator** to choose controller. (This popup menu is only displayed if you have loaded controllers.)
- The tank levels and the reference signals are plotted in the upper graph, and the control signals are plotted in the lower. The upper graph is scaled in percentage of full tank, so that 100 corresponds to 25 cm. The lower graph is scaled in percentage of maximal control signal, so that 100 corresponds to 15 V.
- In the popup menu **Operational Mode** you can switch between manual and automatic control.
- In order to change the manual control signal you could either pull the handle or type directly in the box.

- To change the reference value you can either pull the handle or type directly in the box.
- By right-clicking at an axis, a dialog box for zooming is opened. You can also use the capture button to study and zoom collected data.
- The **Time Offset** at the bottom to the left shows the time between 0 and the time displayed on the x axis. To obtain the true time at the x axis, you therefore add the offset value. (The time $t = 0$ is the time when you start the program using the green start button.)
- The **Capture** button is used to study collected data during operation. Click on the button to obtain a figure with reference signals and measured signals. (Use the zoom tool in the figure menu to zoom).
- Save data by clicking on the capture button. Then you obtain a box where you can save data. The data (time, measured signals, reference signals and control signals) is saved as `data.mat`. If you already have a file with that name, the name becomes `data1.mat` etc up to `data3.mat`. (After that you have to use another folder). The data is loaded into MATLAB with the function `load dataX.mat`.

A.4 How to disconnect the four-tank process

When disconnecting the four-tank process it is very important that the middle size holes are screwed in the upper tanks. Check this and therefore go through the items below:

1. Empty the large water bowl and put it on top of the cupboard at the back of the hall.
2. Disconnect the tubes between two double-tank processes.
3. Make sure that no tube is connected to “Out 2”.
4. Connect a tube to “Out 1”, put it through some hole so that it comes out at the back of the process, and then through the hole which is just above the upper tank. Then put the tube into the upper tank. Do this for both processes.
5. Remove the cables of the right UPM from the I/O card of the left computer. Also, disconnect the right process by disconnecting the two cords connected to it.
6. Put back each process (with its UPM) at its original spot and put a blue water bowl under each double-tank process.
7. Connect the level sensors to each tank¹¹ at the card’s “Analog Input kanal 4” and “Analog Input kanal 5” respectively. (The yellow at 4 and the white at 5.)
8. Connect each control signal ¹² to “Analog Output kanal 0” at each I/O card.
9. Finally, connect the two non-connected cords¹³ from the right UPM to the right process.

¹¹The yellow and white sockets, (marked with 1 and 2 respectively), at the broad cord with 4 channels connected to “To A/D” at the UPM

¹²The black cord connected to “From D/A” at the UPM.

¹³The black cord connected to “To Load” at the UPM and the gray cord.