Automatic Control – Basic Course

Laboratory Exercise 1

PID Control

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Practical Things

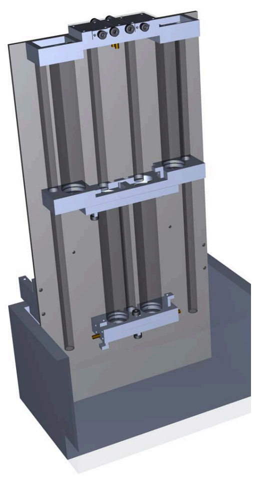
You log in using the account name `lab_tanka`. Leave the password field empty. The two windows of the graphical user interface are opened automatically at login together with MATLAB, running in console mode.

Write down your results in the supplied fields during the lab. You will need these during lab 2.

1. Introduction

The purpose of this lab is to provide understanding of fundamental concepts and principles in automatic control. We will also get acquainted with the PID controller, being the most commonly occurring controller in industry.

The lab process consists of a pump and two tanks connected in series. The process actually consists of two pumps and four tanks, but we will only use the left half of the setup, shown in figure 1. The PID controller, with which we will control the water level in the tanks, is implemented in a PC.



Figur 1: Lab setup (of which the left half is used).

Preparations

In order to get as much as possible out of the lab, you should be familiar with the following concepts:

- open and closed loop system
- block diagram
- set point (reference), measurement and control signal

You should also have read through this lab manual.

Study appendix A, B, explaining the user interface, prior to continuing with the lab. Make especially sure that the valves of the process are correctly positioned according to the instructions in the appendix. Ask your lab assistant if anything is unclear.

2. Fundamental Concepts

This section deals with important concepts in automatic control. We will also get acquainted with properties of the process by manually controlling the water level in the tanks.

What is Good Control?

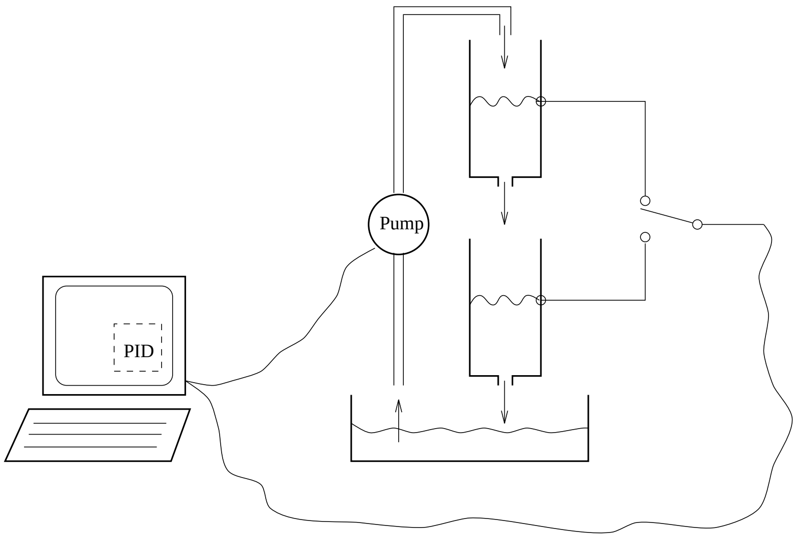
The reason one wishes to control a process is to have it behave in a desired way. This may involve the process becoming more accurate, more reliable or more economic. In some cases the uncontrolled process is unstable and good control is necessary in order not to damage it (which sometimes can cause extensive damage). Hence, good control can mean different things in different applications. When it comes to the tank process of this lab, the following requirements could be appropriate:

- We obviously want the actual water level in the tank to coincide with the desired level (such that measurement = reference).
- If the reference changes, we want the tank level to settle quickly at the new value, without large oscillations.
- The control should be able to handle load disturbances such as external flows and measurement noise, i.e. disturbances acting on the measurement signal.
- Finally, we desire the control signal to the pump not to be extensively "jerky" since this leads to unnecessary wear.

These properties are important in most applications. Can you think of further requirements one would like to put on good control?

Examination of the Process

Assignment 2.1 Get acquainted with the lab setup, cf. appendix A. How can load disturbances be introduced? Is there any measurement noise and if so, can we affect how much? Mark the process, controller as well as the control and measurement signals in Figure 2.



Figur 2: Lab setup

Block Diagram Representation

In order to describe a control system it can often be appropriate to utilize block diagrams. The block diagram provides a schematic view of the system, where features of sub-systems have been abstracted away. In this case we are interested in the relation between reference, measurement and control signal.

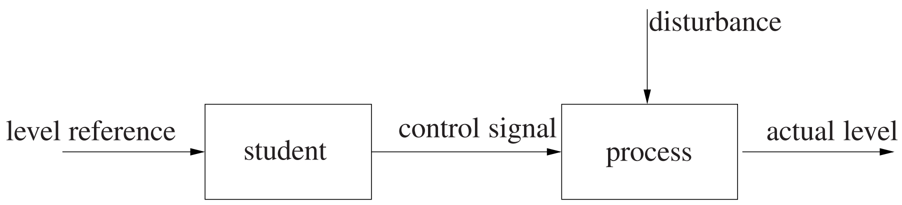
By means of the block diagram, it becomes easier to understand and analyze the process. It is crucial that you understand the relation between the physical process and the corresponding block diagram.

Assignment 2.2 Draw a block diagram of the lab setup, for the case when a controller is governing the level in either of the tanks. Point out the process, controller, measurement signal and control signal in your diagram.

Convince yourself that you understand the relation between the components of your block diagram and the part of the real process.

Open Loop Control

There is a distinction between open loop (lookup table) and closed loop (feedback) control. Under open loop control, the control signal does not depend on the measurement signal. Instead, the control signal is based on a model or table lookups, similar



Figur 3: Open loop system

to what is demonstrated below. Hence, in our case, open loop control means that the level control is not based on observations of the current water level.

Prior to experimenting with open loop control, we must construct a simple model of the tank process. Log in using the account information provided in the beginning of the manual (if you have not already done so). The controller should now be in manual mode. This enables you to directly set the control signal (which is proportional to the pump voltage) and thereby the flow to the upper tank.

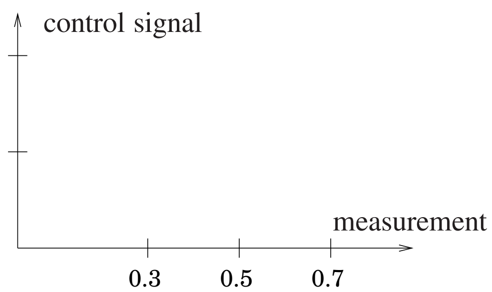
Assignment 2.3 Adjust the control signal (the slider labeled `um`) to correspond to a measurement signal of approximately 0.5 in the upper tank. Use the plot to confirm that the measurement signal y has reached stationarity. It is not important that you obtain *exactly* the prescribed measurement signal. Rather, you should write down the measurement signal you obtain (in the *vicinity* of 0.5) which was reached in stationarity and the value of the corresponding stationary control signal.

Comment: Either of the two graphical user interface windows can be used to read the control signal and measurement signal, respectively. Identify how this is done prior to continuing with the laboration. (Ask the assistant if you feel uncertain regarding the user interface.)

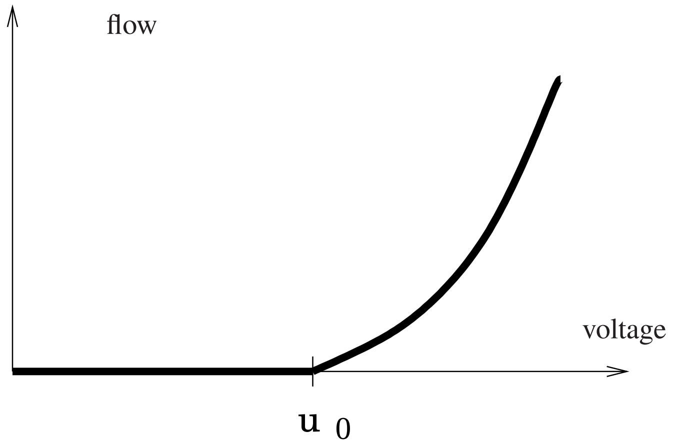
Repeat the experiment for the measurement values (approximately) 0.3 and 0.7, respectively. Transcribe your measurements to the below diagram, plotting the control signal as a function of the corresponding stationary water level. Do not forget that the curve should go through the origin. Why? Can you explain the shape of the curve? We can assume that the flow through the pump is proportional to the pump voltage. (What can be a reasonable explanation if the shape of the curve does not coincide with your expectation?)

Hint: Compare with exercise 1.5 from the course.

measurement	control signal

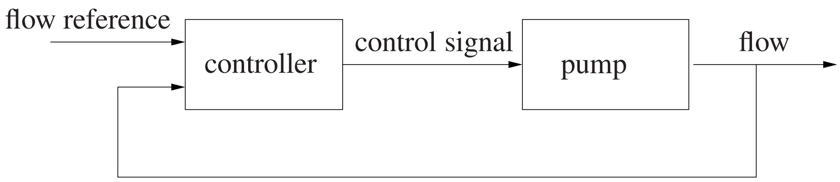


Comment: The actual pump characteristics are not linear from voltage (control signal) to flow. A qualitative illustration of the actual characteristics is shown in Figure 4.



Figur 4: Pump characteristics

Low voltages result in no flow. Voltages above u_0 yield a flow, which increases approximately quadratically with the voltage. In order to hide this inconvenient nonlinearity a cascaded controller is used in this laboration. The pump flow is measured using a Venturi-tube and an inner controller (hidden from the user) ensures that the flow follows the reference given by the user, i.e., you. See Figure 5.



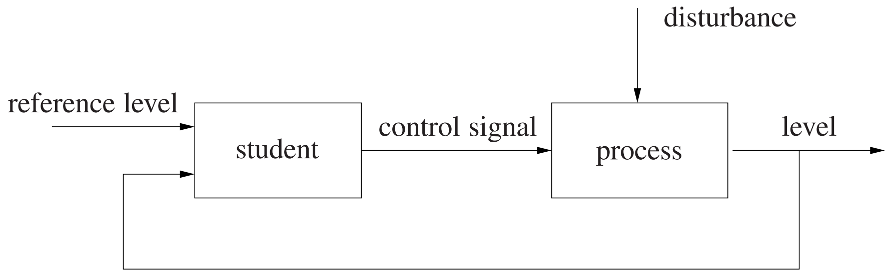
Figur 5: Inner pump flow control loop

Assignment 2.4 Adjust the control signal `um` so that the measurement signal `y` from the upper tank settles at 0.5. Try, using the model from the previous assignment, to increase the measurement signal to 0.8 by means of `um` while your lab partner is obscuring the physical process and the part of the screen showing the measurement signal. What happens if your lab partner opens `BV1` without notice?

Closed Loop Control

You now have access to the measurement signal y and your visual impressions can be used to create a *feedback* connection in order to control the level, cf. Figure 6.

Assignment 2.5 Once again try to increase the measurement signal from 0.5 to 0.8. What limits the time it takes to alter the level? Observe that you are still intended to control the tank manually, i.e. using the `um` slider.



Figur 6: Closed loop system

Subsequently try to keep the tank level constant while your lab partner generated load disturbances using `BV1`. What is preferable, open or closed loop control? Why?

Comparison between the upper and lower tank

We shall now study how level control of the upper tank differs from level control of the lower tank.

Assignment 2.6 Switch to the lower tank by toggling `Tank Selection` from `Upper` to `Lower` in the user interface and repeat the experiments from assignment 2.5. What is now limiting the performance (speed)?

Which tank is easiest to control? Why?

3. Control

We shall now use different controllers to control the levels in the tanks. A controller compares the actual value with a reference and computes an ”adequate” control signal. In Appendix C, a P& I (Process and Instrumentation) diagram is presented. It is useful to get a more detailed description of the control strategy.

P Control

To start with, a proportional (P) controller is engaged by toggling `Control Mode` from `Manual` to `Automatic`. If you have done no previous changes, the `P` block in the block diagram of the PID controller will be active (white) while the `I` and `D` blocks are inactive (light blue). (Click on a block to toggle between active and inactive.)

The control signal u is computed as

$$u(t) = K\left(r(t) - y(t)\right)$$

where r is the reference and y the measurement. In our case this means that the pump voltage becomes proportional to the control error $e = r - y$. The constant K is the gain of the controller.

Assignment 3.1 We shall now investigate how the properties of the controller depend on the gain K. Return to the upper tank and set the reference to `r`$= 0.5$ prior to each experiment.

Investigate how well the level tracks reference changes. Start with `K`$= 5$. Increase the reference to `r`$= 0.7$. Wait until the level becomes constant and then reset the reference to `r`$= 0.5$. Are the results to positive and negative reference changes symmetric?

Repeat the experiment for $K = 3$ and $K = 10$. How does the control error and speed depend on the gain K?

Now increase K to 20 and repeat the above described reference change. Does the result differ from that corresponding to $K = 10$? Explain.

Study how the system behaves at load disturbances. Generate step-disturbances by means of the lever `BV1` and impulse disturbances by pouring water directly into the upper tank. How does the behavior change with varying K?

How is the system affected by measurement noise? Vary the gain K and study especially the behavior of the control signal. Give a reasonable value for K.

Assignment 3.2 Next we will experiment with P control of the lower tank by changing `Tank Selection` from `Upper` to `Lower`. Repeat the experiment in assignment 3.1. Try with e.g. $K = 1,\ 3,\ 10$.

Assignment 3.3 Discuss the difference between P control of the upper and lower tank. Are the results satisfactory? Any issues? Give reasonable values for K in either case. What limits K in either case?

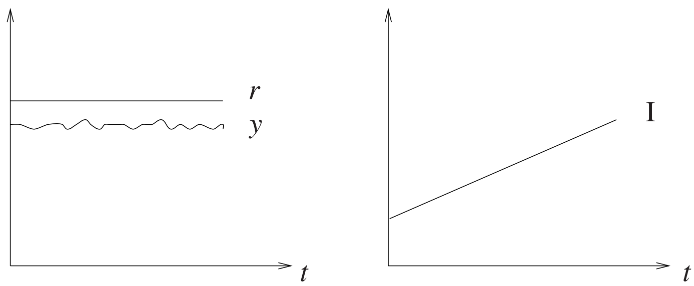
PI Control

A problem with P control, which we have already witnesses, is that it gives rise to a persisting control error. It is natural to increase the control signal while the measurement is lower than the output, in order to eliminate this error. One way of doing this is to let the control signal depend also on the integral of the control error. In a PI controller, u is computed as

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right)$$

where e is the control error, i.e., $e = r - y$. The pump voltage is now given as the sum of two terms. The first one consists of a constant K times the control error and is called the P part (cf. P controller). The second term is a constant K/T_i times the integral of the control error. This part of the sum is hence refered to as the I part (integral part) and changes as long as the reference and output differ, see Figure 7.

T_i is called the integral time, since it is of dimension time. Observe that T_i does *not* affect the integration bounds.



Figur 7: The I part changes as long as the control error presides.

If the control signal u saturates, i.e., reaches its max or min value and a non-zero control error e persists, problems can arise in connection to the integral part since it continues to grow despite the control signal saturation. Once (if) the control error vanishes, a large overshoot or even instability might result, due to the excessively large accumulated integral part. The phenomenon is called integrator wind-up. The lab software contains a built-in wind-up protection, a so called anti-windup scheme.

Assignment 3.4 Experiment with PI control of the upper tank. Vary the integral time T_i and study how the system responds to reference and load changes. Let $K = 5$ and change T_i from 20 down to 1.

Assignment 3.5 Experiment with various values of K and T_i. Give a reasonable PI parameter tuning. Which are the pros/cons compared to P control?

Assignment 3.6 Try PI control of the lower tank. Can you find suitable values for K and T_i.

PID Control

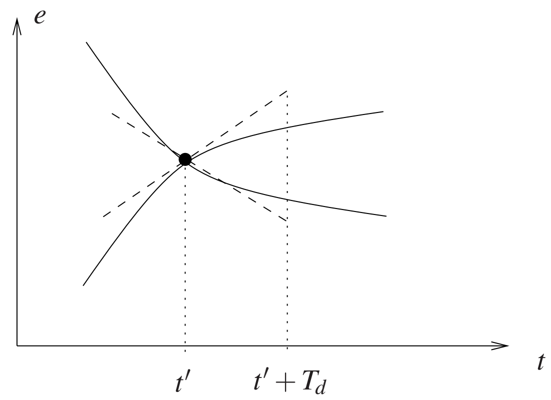
To achieve good control performance, additional insight into the system might sometimes be needed. For example, the derivative of the control error gives an estimate of future error values, see Figure 8. By letting the control signal depend also on the error derivative, one obtains a control law where the control signal increases when the error is growing and vice versa. This can be used to counteract growing control errors in a faster manner and give smoother control action in the vicinity of the reference. If we expand the control law to incorporate derivative action, we obtain the PID controller with control law

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right)$$

The control signal now consists of a P part, an I part and a D part. The D part is given by $(KT_d\frac{de}{dt})$. The constant T_d is the derivative time of the controller. It can be interpreted as the prediction horizon for a linear error estimator, see Figure 8.

Assignment 3.7 First try to control the upper tank using a PID controller. Start out with the best K and T_i values found in the PI case. Does performance increase or decrease with the addition of derivative action. Explain.

Assignment 3.8 Try to find a good PID tuning for level control of the lower tank. Set out with the PI tuning found previously. Investigate the role of the D part by varying T_d from 5 to 50. Conclusions?



Figur 8: The derivative part is used to estimate future control errors.

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4. Tuning Methods

We have now witnessed how changes in the P, I and D parts affect the behavior of the control system. This is naturally of great help, but when tuning a controller one also needs suitable initial values for K, T_i and T_d. If the process to be controlled is slow, one might have to wait hours, or even days, between experiments.

Model Based Controller Synthesis If a mathematical model of the process is available, it can be used to compute controller parameters. This is usually refered to as model based synthesis and will be treated in laboration 2.

Experimental Methods Another way to obtain controller parameters is by performing simple experiments, yielding knowledge of the process dynamics. Subsequently, known rules of thumb are used to tune the controller. The experimental methods do not guarantee a suitable controller tuning but often result in a descent starting point for further tuning. The perhaps most used, but not necessarily the best, methods are those of Ziegler and Nichols.

Auto-tuning some commercially available PID controller have built in functions for automatic controller tuning. These functions are often based on experimental methods.

Assignment 4.1 Demonstration The lab assistant demonstrates (if time allows) how a commercial controller can be used for controlling the tank process. Especially, automatic tuning is demonstrated.

5. Summary

Assignment 5.1 Summarize the most important differences between open loop (manual control, lookup table) and closed loop (feedback) control.

Assignment 5.2 Discuss the pros and cons of P, PI and PID control of the upper and lower tank, respectively. Especially, answer the following questions and complete the below table.

How does a too large/small K affect control performance? (How does the response to reference and load changes behave? How does the control signal and the stationary error behave?)

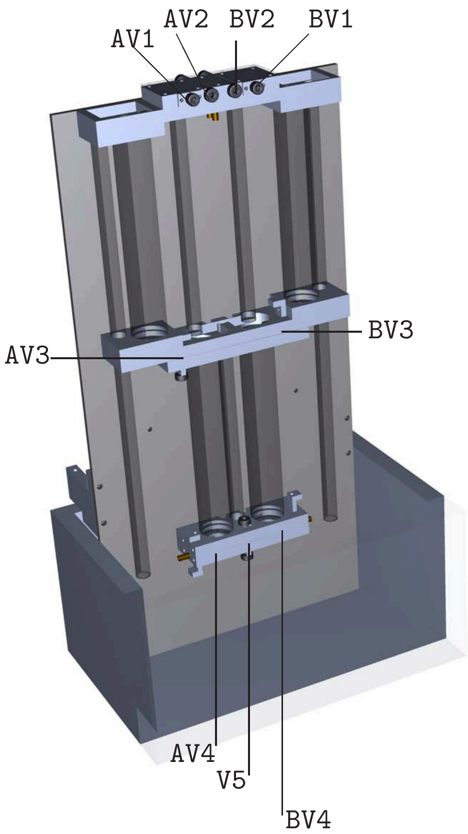
What happens to the control performance if the integral time T_i is small/large?

How does the derivative time T_d affect the control performance? Is there any difference between the upper and lower tank?

Table of suitable controller tunings (bring it to laboration 2!)

	upper tank	lower tank
P	K =	K =
PI	K = T_i =	K = T_i =
PID	K = T_i = T_d =	K= T_i = T_d =

We have dedicated this laboration to level control of the tank system. Mention some other control problems that can be treated in the same way as in this laboration.



Figur 9: Controls of the laboration process

A. Physical User Interface for Laborations 1 and 2

This appendix deals with the hardware and software interface used in laborations 1 and 2.

Controls

Figure 9 shows a picture of the laboration process. During this laboration, we will use controls `BV1`, `AV3`, `AV4`, which shall be pressed in/down at the start of the laboration. **Controls `AV1`, `AV2`, `BV2` shall be pressed in while `BV3`, `V5`, `BV4` shall be pressed down.** This is important in order for numerical values in the manual to coincide with those in reality.

B. Graphical User Interface for Laborations 1 and 2

Below follows a short description of the software interface used during the tank labs. The interface consists of two windows: the ”Process” and ”Controller” window, respectively.

The Process Window

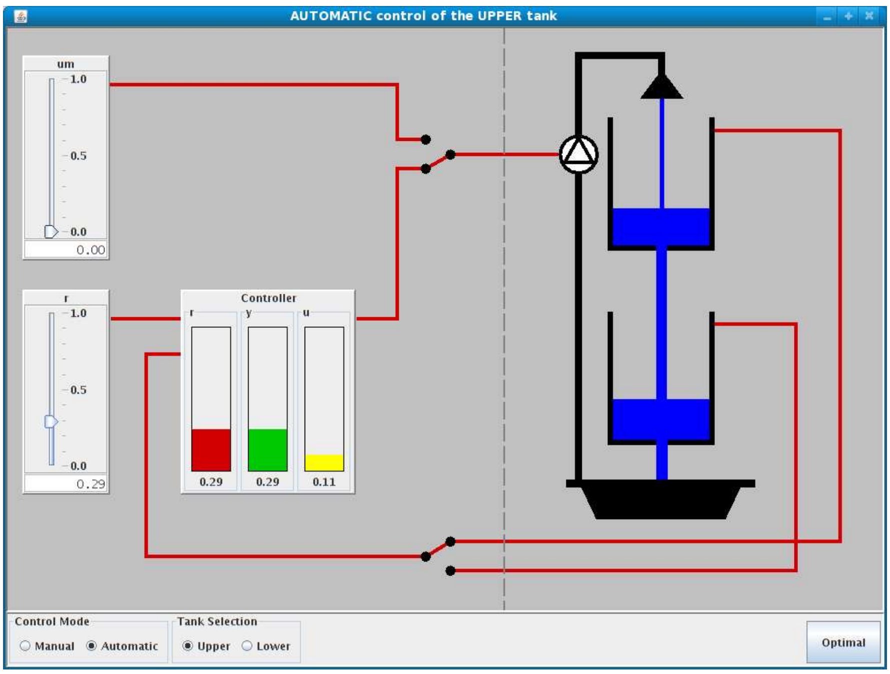
This window gives an overview of the process and shows the interconnection between the process objects, see figure 10. Physical objects are shown to the right of the vertical central line. For example, a picture of the pump and an animations of the water tanks are shown. To the left of the central line, objects implemented in the computer are shown. The most important of these are the PID controller. But there are also various controls and switches.

By using the mouse or keyboard one can carry out the following operations:

Manual/PID. By clicking on the upper switch, one toggles between manual and PID control of the pump. The current mode is indicated by the title bar of the window and the routing of the virtual wires.

Upper/Lower tank. By clicking on the lower switch, one toggles between control of the upper and lower tank. I.e, whether the measurement signal should come from the upper or lower level sensor. Also this is shown in the title bar of the window and on the routing of the virtual wires.

Manual control. The control marked `um` is used to directly control the pump in manual mode. The value is changed by dragging the triangle to a desired location, using the mouse. Alternatively, one can click in the box and enter a desired value.



Figur 10: Process View.

Reference. The control marked `r` is used to adjust the reference of the controller (between 0 and 1). The value is changed in the same way as described above.

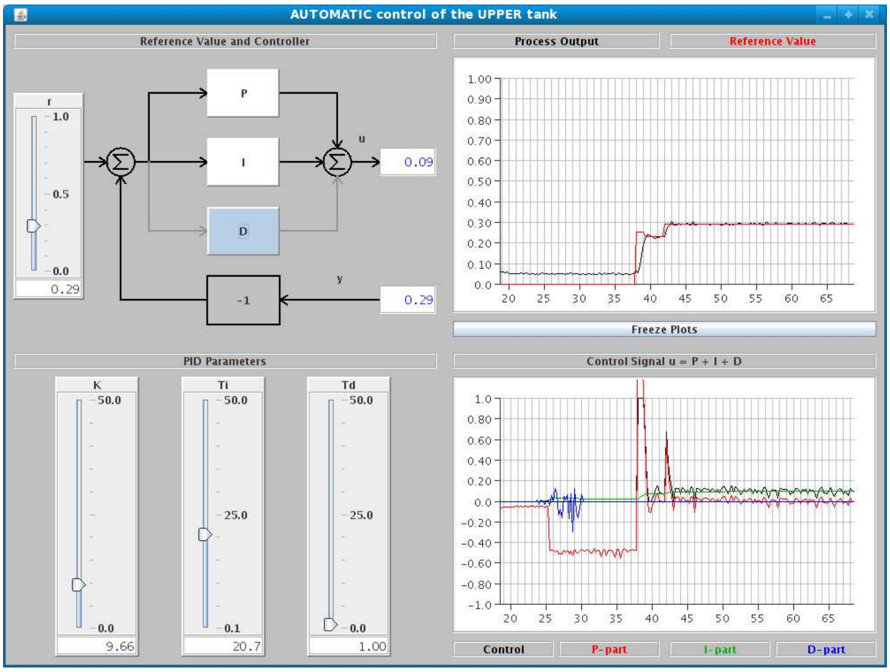
Optimal. This function is only available in `Control Mode` - `Automatic` with `Tank Selection` - `Lower` (closed loop control of the lower tank). A time optimal controller is used to bring the lower tank level to the reference `r` as fast as possible and the upper tank level to the corresponding stationary equilibrium. Once this is achieved, the controller automatically switches back to PID control. (It is also possible to abort the time optimal control by pressing the `Optimal` button.) The button can be used to rapidly ”reset” the process between consecutive experiments involving control of the lower tank.

The Controller Window

This window shows the structure of the controller. It also shows reference, measurement and control signals in two separate diagrams. The top left part shows a block diagram of the controller. By clicking the different blocks one can activate or deactivate the P, I and D parts indecently. In figure 11 the P and I parts are active yielding a PI controller. The slider marked `r` is used as previously to set the reference. At the bottom right, there are three sliders marked `K`, `Ti` and `Td`, used to alter the controller parameters.

The title bar of the window indicates whether the upper or lower tank is controlled and whether manual or automatic control is used.

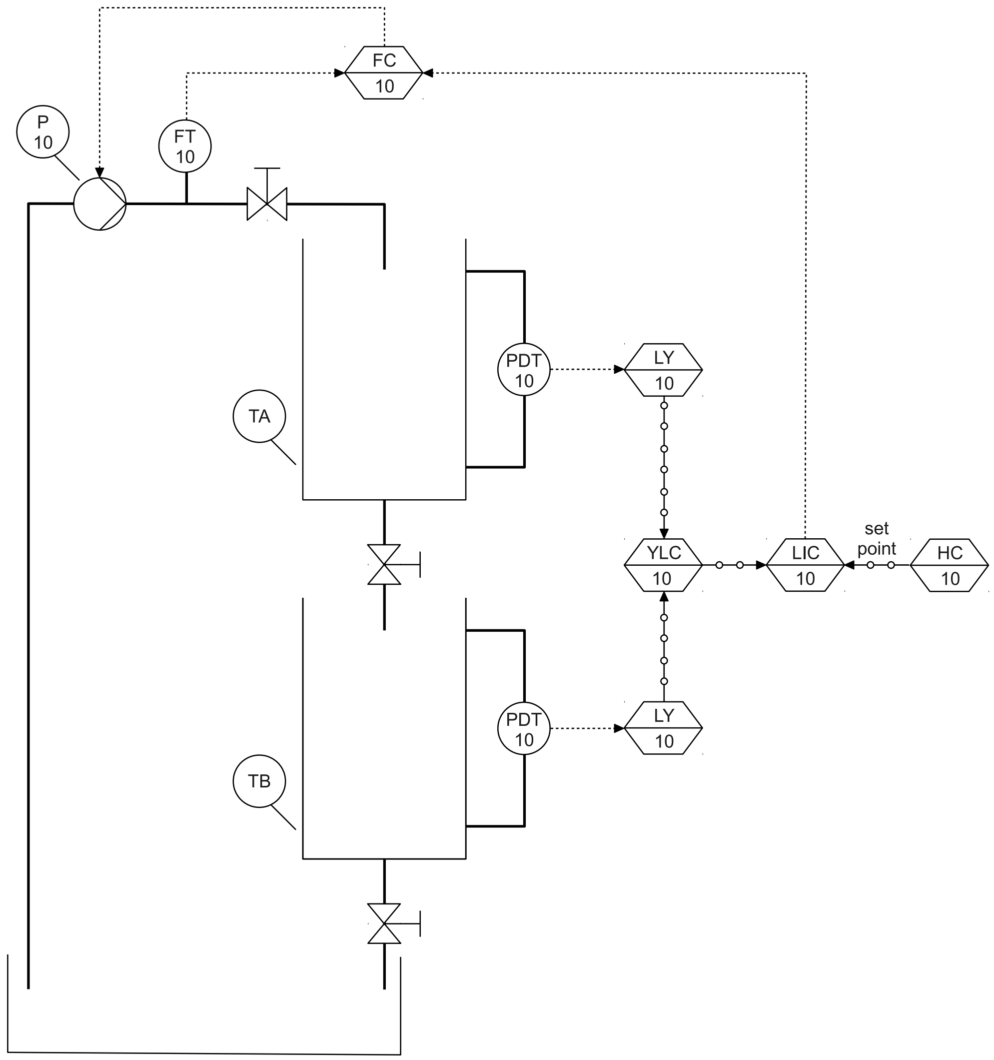
The right side of the window hosts two plots. The upper one shows the reference `r` and the measurement `y` while the lower one shows the control signal `u` and its components `P` `I` and `D`. The time axis are graded in seconds. The plots may be frozen using the ”Freeze Plot” button.



Figur 11: Controller View.

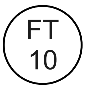
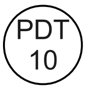
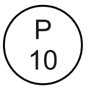
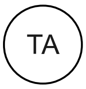
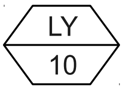
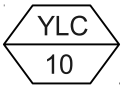
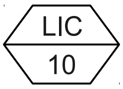
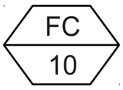
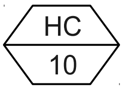
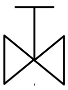
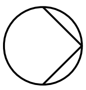
C. P & I diagram of the tank process

Figure 12 shows the P& I diagram (Process and Instrumentation diagram) for the tank process, according to the Swedish Standard SS-ISO 14617 part 1 to 10.



Figur 12: P & I diagram of the tank process

Tabell 1: Symbol Description

	Flow transmitter in control loop 10. Stand-alone field mounted element (circle).
	Differential Pressure Transmitter in control loop 10. Stand-alone field mounted element (circle).
	Pump in control loop 10. Stand-alone field mounted element (circle).
	Tank A.
	Level converter (Y) in control loop 10. Computer function (hexagon) board-mounted accessible for monitoring (solid line).
	Switch (Y) for Level Controller in control loop 10. It determines which level signal (Tank A or B) is sent to the input of the level controller. Computer function (hexagon) board-mounted accessible for monitoring (solid line).
	Level Indicator Controller in control loop 10. Computer function (hexagon) board-mounted accessible for monitoring (solid line).
	Flow Controller in control loop 10. Computer function (hexagon) board-mounted accessible for monitoring (solid line).
	Manual (H) set point Controlling in control loop 10. Computer function (hexagon) board-mounted accessible for monitoring (solid line).
	Valve manually actuated.
	Pump.
	Thick solid process line. It shows the process piping.
	Software link.
	Electric line.