

# Automatic Control – Basic Course

## Laboratory Exercise 1

### PID Control

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## 1. Introduction

The purpose of this laboratory exercise is to give insight into elementary concepts and principles in automatic control. We shall also get closer acquainted with the PID controller, the industrially most commonly occurring controller.

The lab process consists of a pump and two serially connected tanks. A PID controller is implemented in a PC, which will be used to control the water level in the tanks.



Figure 1 Lab setup.

### Preparations

To get out as much as possible of the lab you should know the following concepts:

- Open and closed loop systems.
- Block diagrams.
- Reference value, process output and control signal.
- Stationary error.

You should also have read through this lab manual, including the appendix on the user interface.

## 2. Elementary Concepts

This section deals with important concepts in automatic control. We shall also acquaint ourselves with the properties of the process by manually controlling the water level in the tanks.

## What is Good Control?

The reason one wants to control a process is to have it behave in a preferred way. This could involve the process to become more exact, more reliable or more economic. In certain cases processes are unstable and good control is necessary to prevent them from breaking (which could cause severe damage).

Consequently, good control means different things for different applications. When it comes to the tank process in this lab, the following requirements on the control could be suitable:

- We obviously want the real tank level to coincide with our reference (so that process output = reference value).
- If the reference value is changed we want the tank level to adjust to the new reference fast and without large overshoots.
- The control ought to handle disturbances in the form of load disturbances, when the process is affected by an external signal, and measurement noise, when the measurement of the process output contains some sort of error or disturbance.
- Finally, we don't want the control signal to the pump to be too "jerky" because this causes unnecessary wear and tear.

These properties are usually important in most applications. Can you think of any other requirements one could impose on good control?

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## Examination of the Process

**Assignment 2.1** Acquaint yourself with the lab equipment. How can we introduce load disturbances? Is there any measurement noise in the process and can we affect its extent? Mark the process and the controller together with control signal and process output in figure 2.

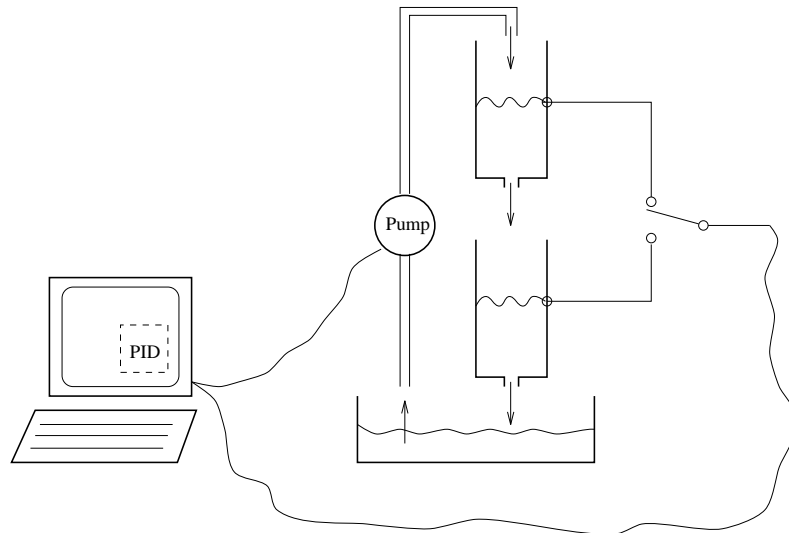
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## Block Diagram Representation

To describe a control system it can often be suitable to use block diagrams. A block diagram is a schematic drawing of a system, where one has abstracted away all properties of the different subsystems, except those one is interested in. In this case we are interested in the relation between reference value, measured process output and control signal.

Aided by block diagrams, one can easier understand and analyze a process. It is of great importance to understand the relation between the real process and the block diagram.



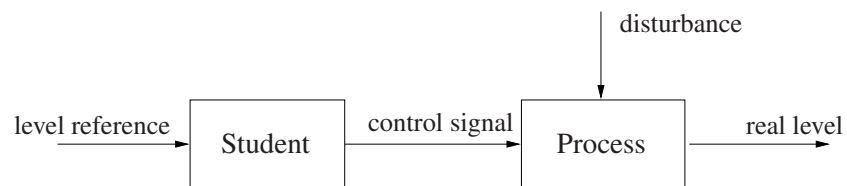
**Figure 2** Lab setup.

**Assignment 2.2** Draw a block diagram for the lab setup when a controller controls the level in one of the tanks. Mark the process, control signal and measured process output also here.

Make sure that you understand the relation between the components in the block diagram and the different parts of the real process.

### Open Loop Control

We differentiate between open loop control (program control, feed forward) and closed loop control (feedback). In open loop control, as opposed to closed loop control, the value of the control signal does not depend on the measured process output. The control signal is instead based on a model or tables similar to the one below. For the tank process open loop control means that we should control the tank level without knowing the present level.

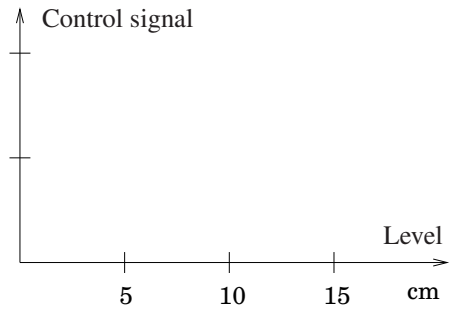


**Figure 3** Open loop system.

Before we experiment with open loop control we first have to construct a simple model of the tank process. Log in according to your lab assistant's instructions. Set the controller to manual mode. You can now directly affect the control signal yourself (i.e. the voltage to the pump) and thereby the flow to the upper tank.

**Assignment 2.3** Adjust the control signal so that the level in the upper tank settles at approximately 5 cm. Note the corresponding control signal in the table below. Repeat the experiment for the levels 10 cm and 15 cm, respectively. Draw a diagram where the control signal is given as a function of the level. (Don't forget that the curve should pass through the origin!) Can you explain the shape of the curve? You may assume that the flow is proportional to the control signal.

Level	Control signal
5 cm	
10 cm	
15 cm	




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**Assignment 2.4** Adjust the control signal so that the level in the upper tank settles at 10 cm. Guided by your model from the previous assignment, try to change the level by approximately 3 cm when your partner obscures the upper tank. What happens if your partner opens the valve without informing you?

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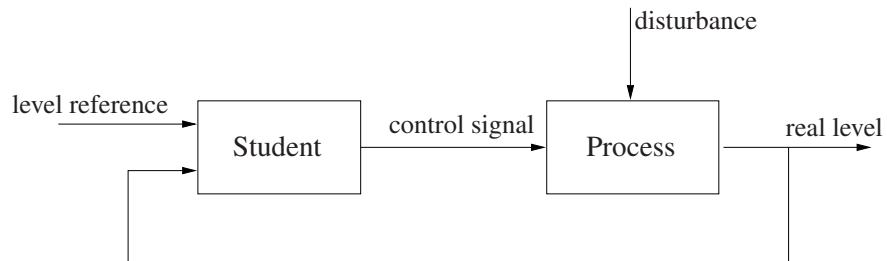
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**Closed Loop Control**

Now you have access to the measured process output, i.e. the real tank level, and your visual impressions can be *fed back* to control the tank level, see figure 4.



**Figure 4** Closed loop system.

**Assignment 2.5** Again, try to change the level by 3 cm. What is limiting how fast you can change the level? Observe that you should still control the tank manually!

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Next, try to keep the tank level constant while your partner generates load disturbances. What is preferable, open or closed loop control? Why?

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In the remainder of the lab we stick to closed loop control.

### Comparison between the Upper and Lower Tanks

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

**Assignment 2.6** Switch to the lower tank and repeat the experiments from assignment 2.5. Obscure the upper tank!

What is limiting the speed?

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Which tank is easier to control? Why?

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## 3. Control

We shall now use different controllers to control the levels in the tanks. A controller compares the reference value with the measured process output and computes an “appropriate” control signal.

### P-control

To start with, we incorporate a proportional controller (P-controller). The control signal  $u$  is calculated according to the following relation

$$u(t) = K(r(t) - y(t))$$

where  $r$  is the reference value and  $y$  is the measured process output. In our case this means that the voltage to the pump is proportional to the control error  $e = r - y$ . The constant  $K$  is usually called the gain of the controller.

**Assignment 3.1** We shall now examine how the properties of the controller depend on the gain  $K$ . Return to the upper tank and set the reference value to approximately 8 cm prior to each experiment.

Examine how well the tank level follows changes in the reference value. Start with  $K = 10$ . Increase the reference value by 3 cm. Wait until the level is constant and subsequently reset the reference value. Is there a difference in behavior between positive and negative change in reference value?

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Repeat the experiment with  $K = 3$  and  $K = 30$ . How do control error and speed depend on the gain  $K$ ?

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Increase  $K$  to 40 and repeat the above changes in reference value. Does the result differ from what we obtained with  $K = 30$ ? Explain!

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Study how the system behaves when load disturbances are introduced. Generate both step disturbances (in the upper tank) by means of the valve and impulse disturbances by pouring water directly into the upper tank. How does the behavior change when  $K$  is varied?

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

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**Assignment 3.2** Now experiment with P-control of the lower tank. Repeat the experiments of assignment 3.1. Try for example  $K = 3, 10, 30$ .

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**Assignment 3.3** Discuss the difference between P-control of the upper and lower tank. Are the results satisfactory? Any problems with the control? Give reasonable values of  $K$  for both cases. What constitutes an upper limit on  $K$ , for the two cases, respectively?

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**To Think About** How could one estimate a reasonable start value for  $K$  if it was not given?

How could one modify the control law of the P-controller so that the stationary error vanishes?

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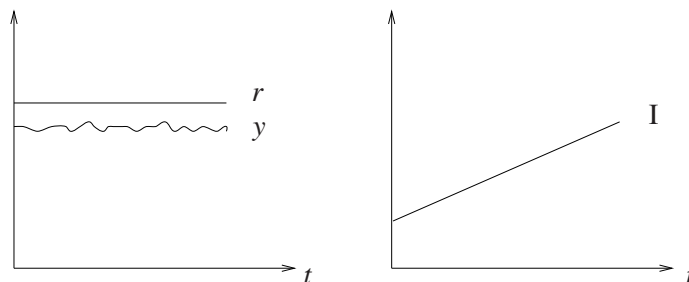
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### PI-control

A problem with P-control is, as we have seen, that one can end up with a persisting control error. To counteract this, it is natural to increase the control signal as long as the reference value is smaller than the process output. A way to do this is to let the control signal depend also on the integral of the control error. In a PI-controller, the control signal  $u$  is calculated according to the relation

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

where  $e$  is the control error,  $e = r - y$ . The voltage to the pump is now given as the sum of two terms. The first consists of a constant  $K$  times the control error and this term is usually called the P-part of the controller (cf. P-controller). The second term is given by a constant  $K/T_i$  times the integral of the control error. This part of the sum is consequently called the I-part (integral part) of the controller, and it changes as long as the measured process output differs from the reference value, see figure 5.  $T_i$  is called the integral time because it has the dimension time. Observe that  $T_i$  does *not* influence the integration limits.



**Figure 5** The I-part is changed as long as there is a control error.

If the control signal  $u$  saturates (reaches its maximum or minimum value) and there is a persisting control error  $e$ , the integral part could impose a problem. It continues to grow and wants to “go at it even harder” despite that the maximal control action is already issued. When the control error has vanished and it is time to crank down the control signal, it remains on its maximum because the integral has grown and obtained a too large value. This phenomenon, which can result in large overshoots or even instability, is known as integrator wind-up. The lab software therefore has a so called anti wind-up protection scheme, counteracting this.

**Assignment 3.4** Experiment with PI-control of the upper tank. Vary the integral time  $T_i$  and study how the responses to reference value changes and load disturbances are affected. Set  $K = 10$  and change  $T_i$  from 50 down to 5.

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**Assignment 3.5** Experiment with different values on  $K$  and  $T_i$ . Give a suitable setting for a PI-controller of the upper tank. Which are the pros / cons compared to P-control?

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**Assignment 3.6** Try PI-control of the lower tank. Can you find suitable values of  $K$  and  $T_i$ ?

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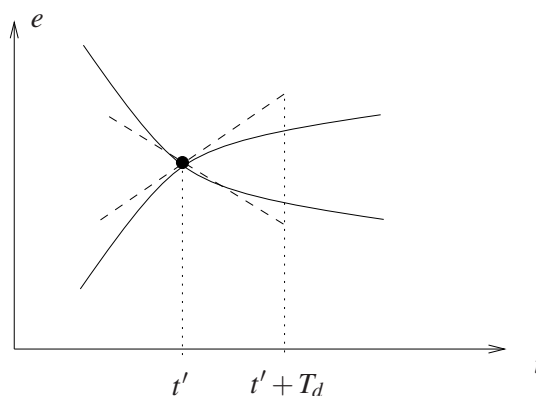
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### PID-control

Sometimes additional information about the process is required to obtain good control. For example the derivative of the control error gives an estimate of future values of the error, see figure 6. By letting the control signal depend also on the derivative of the control error, one obtains a control signal which increases when the error increases and decreases when the error decreases. This results in “smoother” control as one approaches the reference value. If we extend the PI-controller to include derivative action, we obtain a PID-controller where the control signal  $u$  is given by

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

The output of the controller now consists of a P-part, an I-part and a D-part ( $KT_d \frac{de}{dt}$ ).  $T_d$  is called the derivative time of the controller. It can be interpreted as a prediction horizon, see figure 6.



**Figure 6** By means of the derivative part one tries to estimate future values of the error.



**Assignment 3.7** First try to control the upper tank with a PID-controller. Start with the best values found for  $K$  and  $T_i$  when experimenting with PI-control of the upper tank. Does control performance increase or decrease when adding the D-part? Explanation?

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**Assignment 3.8** Try to find a good PID-setting for level control of the lower tank. Start with the best values of  $K$  and  $T_i$  found for PI-control of the lower tank. Examine the influence of the D-part by varying  $T_d$  from 5 to 50. Conclusion?

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## 4. Tuning Methods

We have now seen how the P-, I- and D-parts affect the behavior of the control system. This is of course of great importance, but when tuning the controller one also wants to know what initial values of  $K$ ,  $T_i$  and  $T_d$  should be chosen in order to avoid an all too lengthy tuning process. If dealing with a slow process, one could need to wait for hours, or even days, to evaluate whether the control works satisfactory.

**Model Based Controller Design** If we have access to a mathematical model of the process, we can exploit it to calculate the controller parameters. This is usually called model based controller design and is treated in lab 2.

**Experimental Methods** A different way to obtain controller parameters is to conduct simple experiments to gain knowledge of the process dynamics (behavior). Subsequently, known rules of thumb are used to tune the controller. The experimental methods do not guarantee good controller settings but often give reasonable initial values for the controller parameters. Today there exists a large number of different experimental methods for tuning PID-parameters. The perhaps most known, but not necessarily best, are the Ziegler-Nichols methods.

**Auto Tuning** Today some commercial PID-controllers have built in tuning functions for automatic controller tuning. These functions are often based on some experimental method, cf. the above section.

## 5. Summary

**Assignment 5.1** Summarize the most important differences between open loop control (feed forward, program control) and closed loop control (feedback).

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

How is the control performance affected if the gain  $K$  is small / large? (How is the answer affected by reference value changes and load disturbances? How is the control signal affected? How is the stationary error affected?)

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How is the control performance affected if the integral time  $T_i$  is small / big?

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How is the control performance affected if the derivative time  $T_d$  is small / big? Difference between the upper and lower tank?

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**Table of suitable controller settings (bring this to lab 2!)**

	Upper tank	Lower tank
P	K =	K =
PI	K = $T_i =$	K = $T_i =$
PID	K = $T_i =$ $T_d =$	K = $T_i =$ $T_d =$

## User Interface for Labs 1 and 2

Here follows a short description of the user interface of the software which is used during the tank labs. The interface consists of two windows: the “Process window” and the “Controller window”.

### The Process Window

This window gives an overview of the lab setup and shows how the various process objects are interconnected, see figure 7. To the right of the center line, real world objects are shown. We find for example a picture of the pump and animations of the water tanks together with blocks corresponding to the level sensors. To the left of the center line are the objects which have been implemented in the computer. Most important is the PID controller, but here are also different controls and switches. On the centerline, which constitutes a border between computer and reality, we find blocks which represent D/A- and A/D converters. These convert signals in Volts to digital numbers and vice versa (10 V corresponds to the digital number 1).

By moving the cursor to locations in the window, where there are measurable entities, (electric conductor, tanks with water levels and outflows, etc.) one can see their present values in the “Probe box”, bottom right.

By using the mouse and keyboard the following operations can be carried out:

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

**Upper / lower tank.** By clicking on the lower switch, one can choose whether the controller should control the upper or lower tank, i.e. if the process output

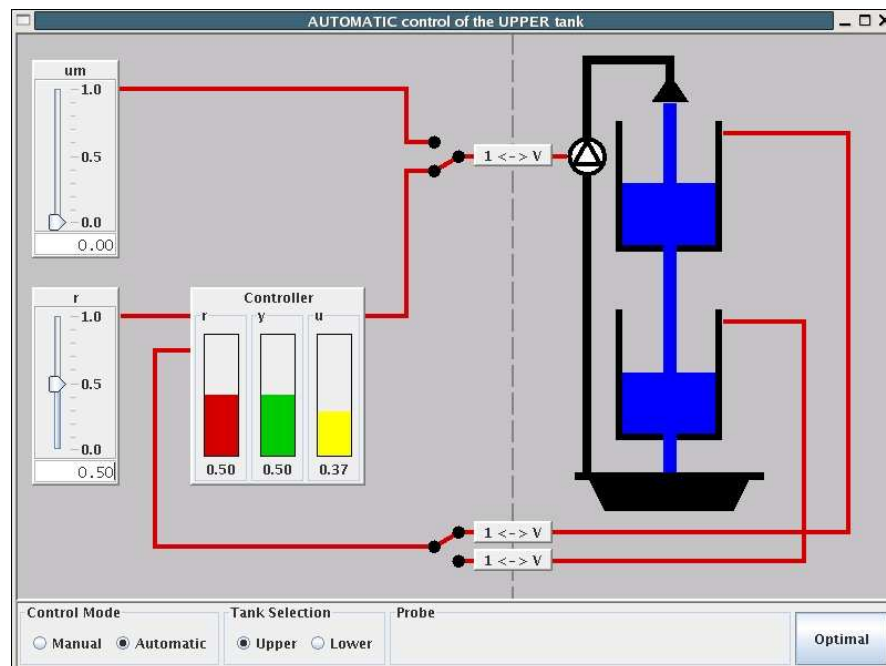


Figure 7 Process View.

measurement should be taken from the upper or lower tank. Also current tank selection is indicated by the window title and the routing of the virtual wires.

**Reference value.** The control marked  $r$  is used to set the reference value (between 0 and 1). The value is changed by pulling the triangle to the desired position with the mouse. Alternatively, one can click in the box where the present value is shown and enter a new value.

**Manual control.** The control marked  $u_m$  is used to control the pump when it is driven manually. The value is changed in the same way as the reference value, cf. the above item.

**Optimal.** This function only works when controlling the lower tank. A time optimal controller is used to change the level in the lower tank to the reference value. The function can be used fast "reset" of the process between two experiments.

### The Controller Window

This window shows the interconnections within the controller. Additionally, reference value and control signal are shown in two diagrams. At the upper left a block diagram of the controller is shown. By clicking the different blocks one can activate the P-, I- and D-parts independent of each other. In figure 8 the P- and I-parts are active, and we have a PI controller. The control marked  $r$  is used as before to set the reference value. At the lower left there are three controls for changing the controller parameters  $K$ ,  $T_i$  and  $T_d$ . Also the title of this window indicates whether the upper or lower tank is chosen and whether the pump is controlled manually or by the controller.

To the right, two plot windows are shown. In the upper the reference value  $r$  is shown, while the lower shows the control signal  $u$  together with its components  $P$ ,  $I$  and  $D$ . The length of the time axis corresponds to 100 seconds when the upper tank is chosen and 400 seconds when the lower tank is chosen. Observe that the upper plot can be frozen using the button "Freeze Plot".

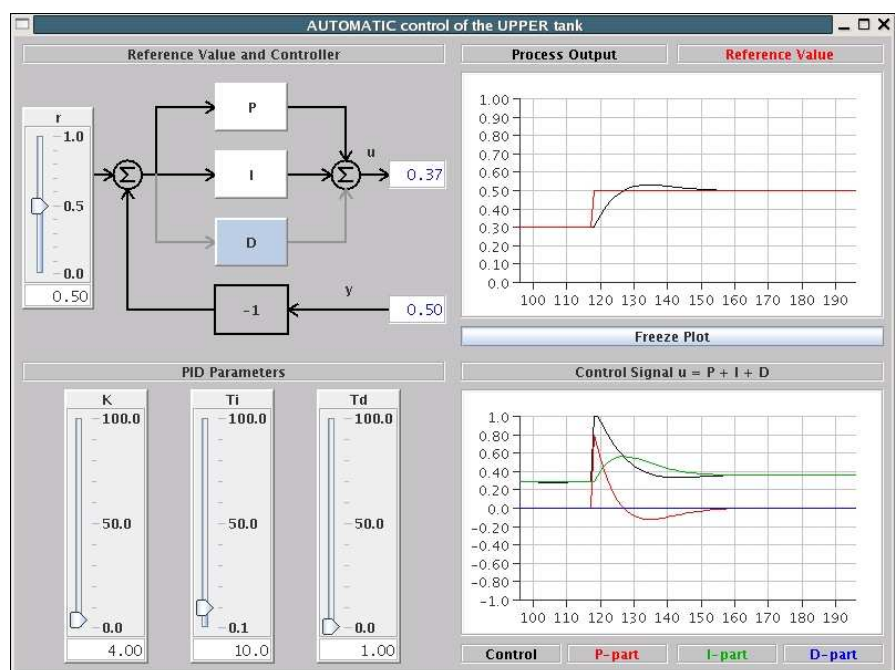


Figure 8 Controller View.