A Teaching Laboratory for Process Control

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A TEACHING LABORATORY FOR PROCESS CONTROL

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ABSTRACT

Laboratory teaching is one possibility to introduce more realism into control education. This paper describes the control laboratory and a sequence of experiments that are performed in the basic automatic control courses at Lund Institute of Technology. The laboratory is based on level control of two cascaded tanks. An Apple II computer is used to implement control laws, graphics, and for computer aided instructions. Four labs of successively increasing complexity are performed. They include empirical experimentation with PI and PID control, modeling and parameter fitting, design, implementation and tuning of PID control, antiwindup, auto-tuning, selector control, state feedback, Kalman filtering and output feedback.

1. INTRODUCTION

The connection between theory and practice is one of the most difficult things to teach in engineering. This problem is particularly accentuated in automatic control where there often is a high level of abstraction. We have for many years been experimenting with different techniques such as demonstrations, projects, special laboratory courses etc., to overcome the difficulties. All students who take a control should have hands on experience of how control system actually behave. About four years ago we started to develop a new process control laboratory. The laboratory is integrated into the basic course in automatic control which is taken by all students in chemical, mechanical and electrical engineering, applied physics and computer science at our university. The laboratory has also been used in extension courses for outside engineers that we give regularly. The laboratory has now been running for two years. Since the experiences have been very good we believe it is worthwhile to present them to a wider audience.

2. GOALS CONSTRAINTS AND ORGANIZATION

The purpose of the laboratory is to demonstrate a number of ideas like:

- The concept of feedback.
- How simple feedback systems work.
- Effects of disturbances and measurement errors.
- When is a control problem easy?
- Process modeling.
- Simple control design techniques.
- State feedback, Kalman filtering and combinations.
- Microcomputer implementation of regulators.

These topics are also covered extensively in our basic course.

The large number of students, limited costs, and limited course time are the major constraints. Last academic year the lab was given to 400 students. Each student can devote 16 classhours to the lab. Since this time is fairly limited it poses constraint on good human engineering.

Costs are a major concern. This applies to investment in equipment as well as the running costs which are mostly manpower. Multiple laboratory setups are required because of the student numbers involved. The lab schedule is also quite tight which means that reliability is another factor.

The basic course in automatic control covers the essentials of feedback from the input-output as well as the state space point of view, see Åström (1976). The laboratory is integrated in the basic course. This was the only way to include a lab because of the competition for classhours with the other departments. The labs are synchronized with the lectures and the problem solving sessions. Four laboratory experiments are made by each student. Time scheduling demands require that all students can go through the labs in a short time period in our case. We run each lab in three four-hours shifts per day for two weeks. The students sign up for the available time slots. We have currently six lab set ups and we allow two students per set up. The synchronization of the lab with the lectures and the problem solving sessions is good pedagogically. It gives practical demonstrations of concepts and theories and practical problems which can be used as motivations for theory development. It also forces the students to review their knowledge to prepare for the lab.

Because of the large numbers involved it is necessary to have many temporary teaching assistants. This poses problems with respect to education of the teaching assistants to ensure that the right message is delivered. We have a detailed lab handbook, see Åström and Östberg (1984), which lab assistants must follow. There are also problems in ensuring that the students are properly prepared. Some novel thinking on the preparation of lab reports have also been made.

3. THE LAB EQUIPMENT

Considerable thought was given to the choice of process. Requirements on a good laboratory experiment for control engineering have been formulated by Balchen et al (1982). These requirements include:

- It should demonstrate important ideas
- It should reflect relevant practical problems
- It should have suitable time scales
- It should give visual and acoustic sensations
- It should be non hazardous
- It should be inexpensive to make and run

In our case the experiments have to be performed by many students with a wide variety of backgrounds. It was therefore crucial that the process dynamics is essentially self explanatory.

After considerable discussion and preliminary experimentation it was decided to choose a simple level control experiment. This satisfies all requirements given above and the dynamics is also easily understood. Level control experiments have also been run successfully used for a long time in many control laboratories, see e.g. Shinskey (1971). Having decided on a process form we also looked at commercially available equipment, see e.g. Wellstead (1979). The available processes were not satisfactory for two reasons, overly simple dynamics and inadequate instrumentation. We therefore decided to make our own equipment.

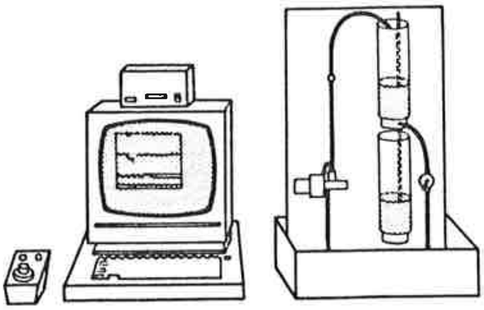

Figure 1 - The laboratory system.

The system used is shown in Figure 1. It consists of two cascaded tanks, made of transparent plexiglass, a sump and a pump. The pump is a high quality gearpump driven by a velocity controlled DC motor. The same pump is used in dialysis machines. We have also built the electronics which convert a standard 0-10 V DC signal to pump speed. The tank levels are measured by capacitive sensors. The sensor signals are converted to standard 0-10 V DC signals proportional to the levels. The electronics is stable so that good calibration coefficients can be given to the students.

The process design allows students to see directly what is happening. The levels are easily visible. Since the water inlet is tilted the inflow can be judged visually. Disturbances are easily introduced simply by adding water to the tanks from a pitcher, and by opening an extra outlet in the upper tank with a manual valve. Measurement noise can be simulated by blowing air into the tanks through a small tube.

Time scales - Considerable thought was given to the choice of time constants. The process should be slow enough so that the students can see what is happening but it should not be so slow that it is boring. The tanks are designed so that it takes 90 seconds to empty a tank and about 30 seconds to fill a tank when the pump motor is running at full speed. A further consideration is that we wanted to make the process slow enough to favor thinking and computing over pure experimentation.

The PC - It is necessary to have control equipment and recorders. We decided at an early stage to use a personal computer for these functions. One reason was that we wanted to introduce digital control from the start. After considering available systems we decided to use an Apple II. This was one of the cheapest, most commonly used computers with reasonable graphics and a wide choice of interface boards. Some preliminary experimentation showed that the relatively poor graphics resolution was adequate. An interface card from Mountain hardware was chosen for AD and DA conversion. This board gives a resolution of 8 bits, which is good enough for our purposes. The low resolution also gives measurement noise in a natural way. A clock card UTIM by U'Microcomputers Ltd. was chosen. This board has the advantage that it does not require a battery. The choice of computer was a good one. When we expanded the lab we were able to get second hand machines very cheaply.

All programming was done in compiled Applesoft Basic. A drawback is that it is not easy to write well structured readable programs. Two character identifiers are not sufficient for readability. Some care in the careful programming ensures that all programs can be run at a sampling rate of at least 10 Hz, which is sufficient.

4. THE EXPERIMENTS

In this section we will briefly describe the experiments performed.

Experiment 1

The goal of the first experiment is to provide empirical experience of simple feedback control. This experiment is scheduled in the second week of the course when the students have had an introductory lecture on automatic control. The students start by exploring the system. They make process diagrams and block diagrams, and continue with simple experiments with manual and automatic control of the tank levels. In particular, they are asked to explore P and PI control of the upper tank including set point changes and load disturbances. They are also required to write down their observations particularily the numerical values of reasonable regulator parameters and step response, static error, etc..

To perform the experiment the students run a pre-programed PID regulator. The screen menu for the first experiment is shown in Figure 2. The different entries are largely self-explanatory. This menu is shown when the system is initiated and different options are chosen by typing the corresponding letter. When the control options are selected the system switches to graphic mode. The process inputs and outputs are then displayed as shown in Figure 3. The system returns to the menu when any key is pressed. The regulator output is then frozen.

Some of the details of the PID algorithm are hidden in the unseen program algorithm, such as how we avoid integral windup, oversensitivity to measurement noise, etc.. At this stage the students see the control as an ideal textbook PID regulator.

```
************************
*  PID REGULATOR       *
************************

ALTER CONFIGURATION (C)
ALTER PARAMETERS    (P)
MANUAL CONTROL      (M)
AUTOMATIC CONTROL   (A)
HARD COPY           (H)
STORE               (S)
QUIT                (S)
```

Figure 2 - Menu for the simple PID regulator.

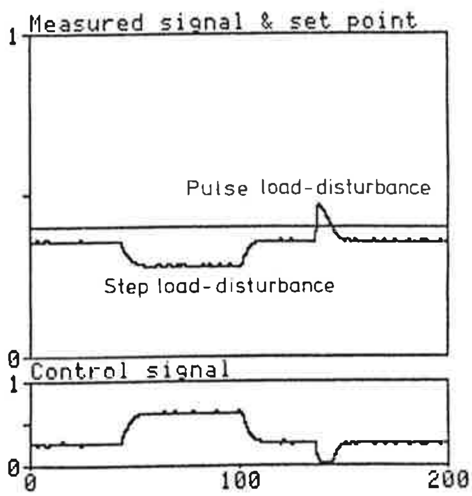

Figure 3 - Process inputs and outputs when the upper tank is controlled by a proportional regulator.

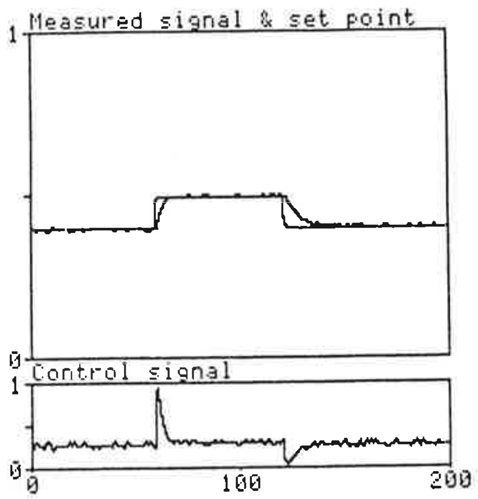

Figure 4 - The upper tank is controlled by a PI regulator.

The dynamics of the upper tank is just a first order lag. Such a process is very easy to control. The gain is limited by the measurement noise. Since both the AD and the DA converter have a resolution of 8 bits it follows that the highest proportional gain is 255. With this gain one bit of the AD converter gives full swing in the output. Figure 3 shows the performance of a regulator with gain 5 with load disturbances. There are bias errors as expected. Figure 4 shows the response of a PI regulator.

It is considerably more difficult to control the level in the lower tank. Proportional control gives a large steady state error. Figure 5 shows the performance of a proportional regulator with gain 5. A PI regulator will not work either, because derivative action is needed to provide reasonable damping. The students discover these properties empirically by experimentation. Because of the intentionally long time constants there will also be a bit of impatience when experimenting with the lower tank. It gives motivation to use rational tuning procedures. When controlling the lower tank the largest gain is determined by the process dynamics.

In summary the first experiment serves to familiarize the students with a simple feedback loop and the characteristics of P, PI and PID control. They should also become familiar with effects of measurement noise, load disturbances and set point changes. They will also obtain reasonable numerical values for the regulator parameters for reference in the following experiments.

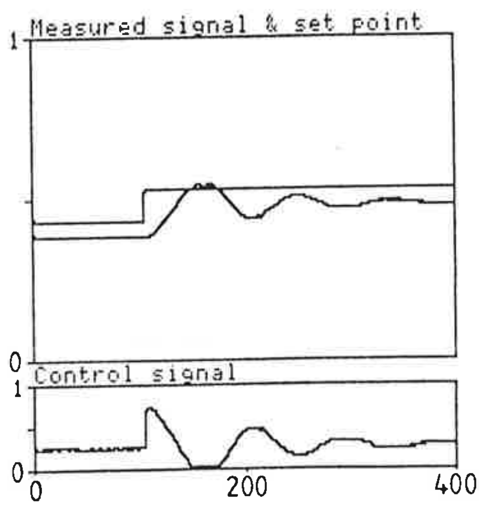

Figure 5 - The lower tank controlled by a proportional regulator

Experiment 2

The purpose of the second experiment is to practice mathematical modeling and to demonstrate that regulator parameters can be computed from a process model.

Modeling Mass balances for the tanks give:

$$\begin{cases} \dfrac{dh_1}{dt} = -\alpha_1\sqrt{2gh_1} + \beta u \\[2ex] \dfrac{dh_2}{dt} = \alpha_1\sqrt{2gh_1} - \alpha_2\sqrt{2gh_2} \end{cases}$$

where h_1 and h_2 are the levels in the first and second tank respectively, α_1 and α_2 are the ratios between the effective outlet areas and the cross sections A of the tanks and

$$\beta = \frac{k_m}{A}$$

where k_m is the constant which relates pump flow to the drive voltage of the pump motor electronics. The drive electronics is designed so that the pump speed is proportional to the input voltage of the amplifier. The actual parameter values differ a little between the different lab stations.

Determination of the parameters - The parameter β can be determined by blocking the outlet of the upper tank and measuring the time it takes for the level to rise from h_ℓ to h_u for a given motor voltage u_o. The parameter α can then be determined by filling the tank and measuring the time it takes for the level to sink from h_u to h_ℓ. There are menu driven programs which assist in determining the parameters.

Linearized Models - The linearized process dynamics can be described by the transfer functions.

$$\frac{H_1(s)}{U(s)} = \frac{k_p T_1}{1+sT_1}$$

$$\frac{H_2(s)}{U(s)} = \frac{k_p T_2}{(1+sT_1)(1+sT_2)}$$

where

$$T_i = \frac{A}{a_i}\sqrt{\frac{2h_i^o}{g}} \quad i = 1,2 \qquad [s]$$

and

$$k_p = \frac{k_m k_c}{A} \qquad [s^{-1}]$$

The parameter k_m $[m^3/Vs]$ is the pump gain and k_c [V/m] the calibration constant for the level sensor.

The linear models will be valid as long as there is no overflow and as long as the pump does not saturate. The expressions for the time constants show how much the dynamics varies with the levels.

Control Design - Having obtained the models it is straight forward to carry out the control design. Since the dynamics of the upper tank is described by a first order dynamics it is sufficient to have a PI regulator. The parameters of such a regulator can be found by pole placement. The desired characteristic equation is then chosen as

$$s^2 + 2\zeta\omega s + \omega^2 = 0$$

Mathematically it is possible to choose any value of the closed loop bandwidth ω. A high value of ω will however give a high gain. In the first experiment it was found empirically that the gain was in fact limited by the measurement noise. This will thus in practice limit the achievable bandwidth.

To design a control system for level control of the lower tank it is first observed that the system is of second order. To control the system well it is clear that a PD regulator is required. To ensure that there are no steady state errors it is necessary to include integral action. The closed loop system is thus of third order. The parameters of a PID regulator can be determined by pole-placement design. The desired closed loop polynomial is

$$(s + \alpha\omega)(s^2 + 2\zeta\omega s + \omega^2) = 0$$

The modeling and the control design are discussed in problem solving sessions before the experiment. The students are required to bring the results of the design calculations to the experiment.

The student have to calculate control parameters by choosing different values of α, ζ and ω and then investigate the closed loop systems obtained. The control design described requires some effort in modeling and control design. To show the students that it is possible to get in the ball park with considerable less effort they are also requested to apply the Ziegler Nichols step response method to tune a PID controller for level control of the lower tank. This results in closed loop systems which are much more oscillatory than the ones obtained by the more elaborate pole placement method.

Summary - The message of this experiment is that it is straight forward to obtain good regulators if a model of the process is available. It is also shown how a model can be obtained.

Experiment 3

Several important details of the PID algorithm have been hidden in the previous experiment. The purpose of this experiment is to exhibit these details and to provide the knowledge necessary to implement control laws using digital computers.

The first issue is how to approach digital control. A simple approach is taken in the introductory course. Most analysis is done in continuous time. The control laws are derived in continuous time form. Discrete time systems are introduced simply via difference approximations. A little difference equation theory is introduced to allow a discussion of stability of digital algorithms. It is also emphasized that such an approach will often work well if we can sample fast but also that we can do better by learning more about digital control, see Åström and Wittenmark (1984).

Another point that we emphasize is the usefulness of a digital computer in other respects besides pure control tasks. Inclusion of design calculations in the regulator code is a typical example. Another thing we can do is to make a self-tuning PID regulator.

Three programs are used for the experiment. The first program PIS1 is a PI regulator for a first order system with built in design calculations. The program inputs are the parameters of the transfer function and specifications in terms of ω and ζ. The students are asked to control the level of the upper tank using this program and to explore

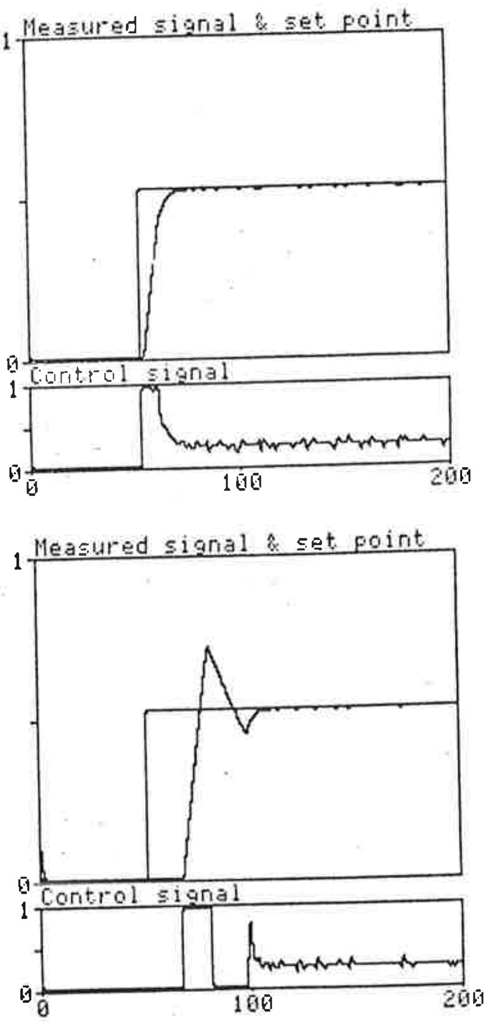

Figure 6 - PI control of the upper tank with and without compensation for windup

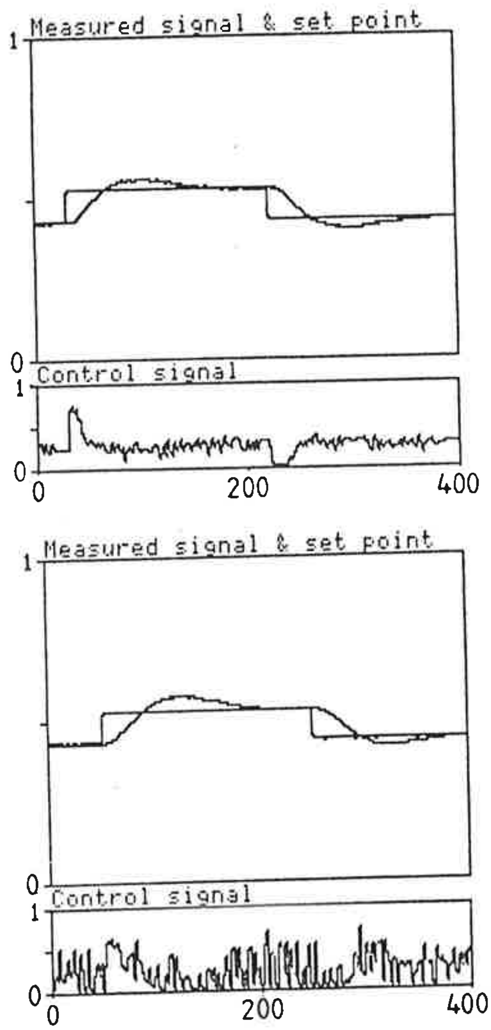

Figure 7 - PID control of the upper tank where the high frequency derivative gain is 5 and 50.

consequences of different choices of pole placement. They are also requested to investigate the sensitivity to modeling errors by introducing wrong data for the process parameters.

The phenomena of integrator windup is also illustrated. How to avoid windup by back calculation is discussed in detail. Figure 6 illustrates windup and control with a PI regulator having antiwindup.

A similar program PIDS2 for PID control of the lower tank is then used to perform analogous experiments with level control of the lower tank.

The details of the digital implementation of a PID algorithm are discussed. This includes limitation of the high frequency derivative gain. Illustration of different high frequency derivative gains with level control of the lower tank is shown i Fig 7. The necessity to have backward differences when approximating the derivative part is demonstrated. The choice of sampling rates are also conveniently explored using the program PIS1. In particular it is shown that the sampling rate is closely related to the choice of closed loop bandwidth.

The last program AUTOTUNE is a program to tune the parameters of a PID controller, see Åström and Hägglund (1984). The students have to compare these results with the results obtained from other design methods.

The computer hardware necessary for control is also discussed. This includes input output programming which are very simple on the Apple II which has memory mapped io. The students are requested to write a small Basic program for control.

Experiment 4

The purpose of the last experiment is to illustrate state feedback, Kalman filtering and output feedback via combination of state feedback and Kalman filtering. The experiments are carried out using one menu driven program with three options, SFBS2 which performs state feedback for a general second order system, KALMAN for the Kalman filter and OFBS2 which performs output feedback for a second order system. There are submenus for each of these tasks.

State Feedback - In this experiment the levels of both tanks are controlled using state feedback from both level measurements. The feedback law is given by

$$u(t) = \ell_1(\gamma r - h_1) + \ell_2\{(r-h_2) + \frac{1}{T_i}\int(r-h_2)ds\}$$

The reference signal is r. Integral action has been added to make sure that there are no steady state errors in the level of the second tank. The feedback gains are determined in such a way that the closed loop system has the characteristic polynomial

$$(s^2 + 2\zeta\omega s + \omega^2)(s + \alpha\omega) = 0$$

Figure 8 shows the response of state feedback. The performance of the state feedback for small perturbations is comparable with PID control using measurements of the lower tank only. The major difference is that there is less variation of the control variable with the state feedback.

Selectors - When the level of the lower tank is controlled by PID control from measurements of the lower level, the upper tank can overflow for large set point changes. This can be avoided with state feedback because the level in the upper tank is measured. A minimum selector is introduced in the algorithm to achieve this. The selector simply measures the deviation of the level in the upper tank from the flooding level. It switches to level control of the upper tank when the level in the upper tank becomes too high.

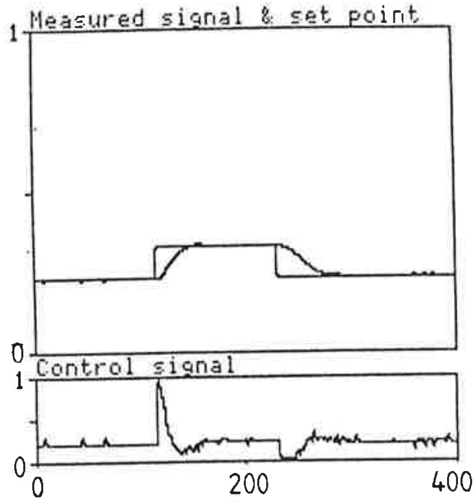

Figure 8 - The level in the lower tank is controlled by state feedback

Kalman Filtering - In the Kalman filtering experiment the pump is controlled manually. The level in the upper tank is determined from measurements of the level in the lower tank and the process model.

The Kalman filter is described by

$$\frac{d\hat{h}}{dt} = \begin{bmatrix} a_1 & a_2 \\ a_3 & a_4 \end{bmatrix} \hat{h} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} u + \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} (y - \hat{h}_2)$$

where the gains are determined in such a way that the characteristic equation is given by

$$s^2 + 2\zeta\omega s + \omega^2 = 0$$

To implement the Kalman filter the differentials are simply replaced by differences. Since the process dynamics is nonlinear the linear approximation which the Kalman filter is based on is only valid in a region around the linearization point. The properties of the Kalman filter are illustrated in Figure 9 which shows the input signal u, the estimated level and the true measured level in the upper tank.

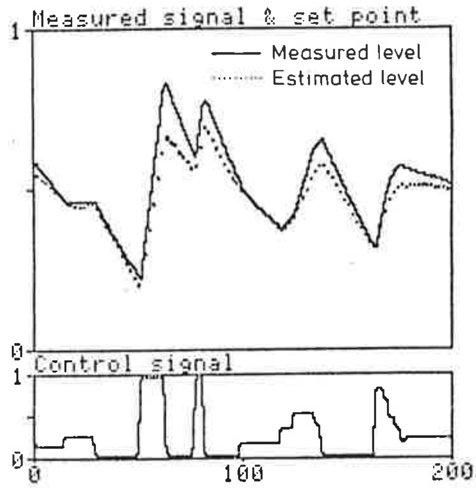

Figure 9 - Estimation of the level in the upper tank using a Kalman filter.

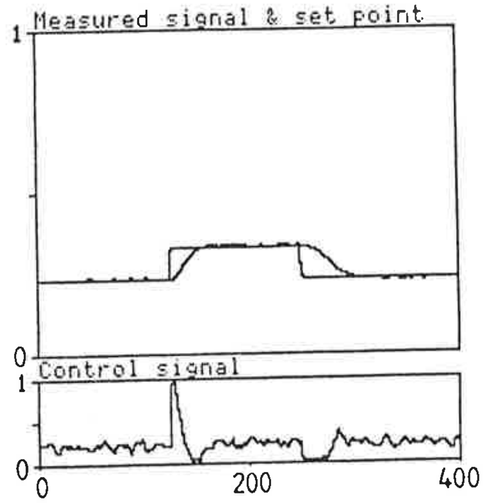

Figure 10 - Results from control based on state feedback and Kalman filtering.

Combination of State Feedback and Kalman Filtering- Output feedback can be obtained by combining the state feedback with a Kalman filter. Because of the separation theorem the parameters obtained in the previous experiments can be used. The resulting regulator is comparable to the simple PID regulator based on measurement of the lower level only. The more complex system can however avoid flooding of the upper tank. It is also less sensitive to measurement noise, see Figure 10.

5. EXPERIENCES

Each lab is coordinated by one supervisory assistant, who prepares the lab and supervises the other lab assistants. He/she has to draw up the time schedules and make sure that there is a lab assistant in each lab. The time schedule has to be available to the students two weeks before the start of the laborations. Our current lab allows 15 lab sessions per week as was discussed in section 2. We have actually run it with 13 sessions per week.

We want to give the same message to all the students in spite of the fact that there are different laboratory assistants. Special lab teaching material is therefore given to the assistants in form of slides, exercises for the lab tests and a special lab handbook. This handbook contains the regular lab material, answers with explanations, equations and calculations, notes, figures and practical hints. The teacher and the lab assistants meet once or twice before the lab to prepare and discuss the problems.

The students have their own lab manual which contains an introduction, instructions for the four experiments, an introduction to Applesoft Basic and tables for documentation of important results. It is practical to have a handbook which includes all the experiments. The students then have all their notes and results available in one place for easy reference in subsequent labs or during a problem solving session.

The students are required to prepare for the experiments. This demands coordination between lectures, problem solving sessions and the lab. As preparation for the second lab, for example, students make a mathematical model of the two casceded tanks and then linearize them. The preparations also include studies of relevant theory and a review of the earlier labs.

Each lab begins with a quizz on the assigned homework. The lab assistant varies problems from lab to lab. These problems cover the theoretical part of the lab. The assistant picks out two problems for the test, eg. to draw a Bode diagram from a given transfer function and linearize a given equation. To avoid unnecessary use of valuable lab time, the assistant checks homework during the test. Students who are not properly prepared are sent home. It is quite important that the students have prepared themselves otherwise they will not get the message and they will take too much valuable time from the other students. Sending home one or two unprepared students at the beginning of a lab seems to yield immediate results in the quality of the lab preparation in future labs.

After the quizz we have a short introduction, where slides are used to summarize the goals and the exercises of the experiment. During this information the students start to concentrate on the lab.

Students get exposed to working with practical control problems in the lab. We have found it favourable to let them work in pairs. This helps in doing the double-checking of caculations, numbers etc. that are so essential in practical work. It also promotes discussions.

Since the setups are easy to handle the assistant does not have to spend his/her time explaining the equipment. Instead he/she can use the valuable time to discuss the exercises and the problems with the students. At the same time he/she can check that the students do all their exercises and make properly notes.

6. CONCLUSIONS

We have had very good experiences of the process control laboratory. It has been very useful in establishing the connections between theory and practice of automatic control and to demonstrate some of the important practical aspects of control that are not covered in normal courses. The lab has been very well received by many different student categories. The fact that the dynamics is essentially self-explanatory is an important factor. The availability of good teaching material has been critical to efficient teaching.

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