A Teaching Laboratory for Process Control

Karl Johan Åström and Ann-Britt Östberg

ABSTRACT: Laboratory experiments offer one way to introduce more realism into the education of automatic control. This paper describes a control laboratory and a sequence of experiments 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 and to provide graphics and computer-aided instruction. Four laboratory experiments 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, autotuning, selector control, state feedback, Kalman filtering, and output feedback.

Introduction

The connection between theory and practice is one of the most difficult lessons to teach in engineering. This problem is particularly accentuated in automatic control, where there is often a high level of abstraction. For many years, we experimented with different techniques, such as demonstrations, projects, special laboratory courses, etc., to overcome the difficulties we encountered. All students who take a control course should have hands-on experience of how control systems actually behave. About five years ago, we started to develop a new process control laboratory. The laboratory is integrated into the basic automatic control course, which is taken by all students in chemical, mechanical, and electrical engineering, and applied physics and computer science at Lund Institute of Technology. The laboratory has also been used in extension courses for engineers from industry. The laboratory has now been running for three years. Because our experiences have been very good, we believe it is worthwhile to present them to a wider audience.

Presented at the 1985 American Control Conference, Boston, MA, June 19–21, 1985. Karl Johan Åström is with the Department of Automatic Control, Lund Institute of Technology, Box 118, S-221 00 Lund, Sweden. Ann-Britt Östberg is with Sydkraft AB Malmö.

Goals, Constraints, and Organization

The purpose of the laboratory is to demonstrate ideas such as:

- The concept of feedback.
- How simple feedback systems work.
- Effects of disturbances and measurement errors.
- When a control problem is 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 major constraints. Last academic year, more than 400 students took the course. Each student spends 16 hours in the laboratory. Since this time is fairly limited, good human engineering of the equipment is a necessity.

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 number of students involved. The 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 [1]. The laboratory is integrated into the basic course. This was the only way to include laboratory experiments, due to the competition for class hours with the other departments. The experiments are synchronized with the lectures and the problem-solving sessions. Four laboratory experiments are carried out by each student. Time-scheduling demands require a high throughput. Each laboratory is run in three 4-hour shifts per day over a two-week period. The students sign up for the available time slots. Currently, there are eight experimental setups, with two students per setup. The synchronization of the laboratory experiments with the lectures and the problem-solving sessions is good pedagogically. It demonstrates behavior and practical problems that can be used as motivations for theory development. It also forces the students to review their knowledge in preparation 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 correct message is delivered. A detailed handbook [2], which describes the experiments in great detail and also gives many practical hints, is given to the assistants. There are also problems in ensuring that the students are properly prepared.

Laboratory 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. [3]. 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 nonhazardous.
- It should be inexpensive to make and run.

In our case, the experiments are performed by many students with a wide variety of backgrounds. Therefore, it was crucial that the process dynamics be essentially self-explanatory.

After considerable discussion and preliminary experimentation, it was decided to choose a simple level control experiment. This would satisfy all the preceding requirements, and the process dynamics is also easily understood intuitively. In addition, level control experiments have been run successfully and used for a long time in many other control laboratories, see [4]. Having decided on a process, we also looked at commercially available equipment, see [5]. The available processes were not satisfactory for two reasons: overly simple dynamics and in-

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adequate instrumentation. Therefore, we decided to make our own equipment.

The system used is shown in Fig. 1. It consists of two cascaded tanks made of transparent plexiglass, a sump, and a pump. The pump is a high-quality gear pump driven by a velocity-controlled DC motor. The same pump is used in dialysis machines. We also built the electronics, which converts a standard 0- to 10-V DC signal to pump speed. The tank levels are measured by capacitive sensors. The sensor signals are converted to standard 0- to 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 introduced simply by adding water to the tanks from a pitcher, or by opening a valve in the upper tank. See Fig. 1. 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 to take 90 sec to empty and about 30 sec to fill when the pump motor is running at full speed. Further, it was desired that the process be 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 (PC) for these functions. One reason was that we wanted to introduce digital control from the very beginning of the course. 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 A/D and D/A conversion. This board gives a resolution of 8 bits, which is satisfactory 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 secondhand machines very cheaply.

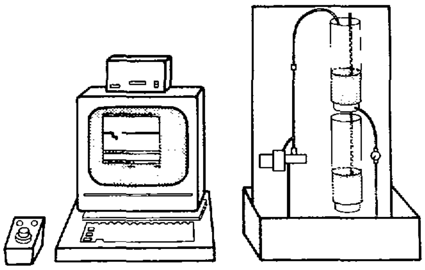

Fig. 1. The laboratory process.

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 programming ensures that all programs can be run at a sampling rate of at least 10 Hz, which is sufficient.

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 for 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 record their observations, particularly the numerical values of reasonable regulator parameters and step response, static error, etc.

To perform the experiment, the students run a preprogrammed PID regulator. The screen menu for the first experiment is shown in Fig. 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. Once the control options are selected, the system switches to the graphic mode. The process inputs and outputs are then displayed, as shown in Fig. 3. The system returns to the menu when any key is pressed. The regulator output is then frozen.

PID Regulator	
Alter configuration	(C)
Alter parameters	(P)
Manual control	(M)
Automatic control	(A)
Hard copy	(H)
Store	(S)
Quit	(Q)

Fig. 2. Menu for the simple PID regulator.

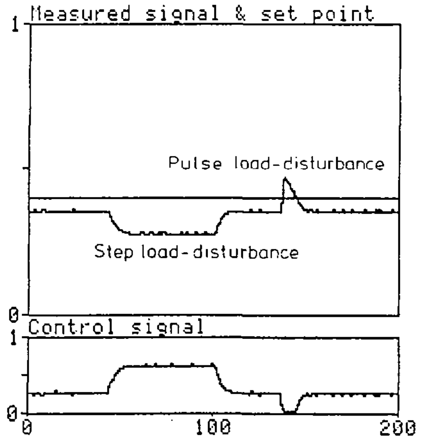

Fig. 3. Results of level control of the upper tank with a proportional regulator. Note the large steady-state errors and the sensitivity to load disturbances.

Some of the details of the PID algorithm are hidden in the unseen program algorithm, such as elimination of integral windup, limitation of derivative gain, etc. At this stage, the students see the control as an ideal textbook PID regulator. More details are shown to the students in later experiments.

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 A/D and D/A converters have a resolution of 8 bits, it follows that the highest proportional gain is 255. With this gain, one bit of the A/D converter gives full swing in the output. Figure 3 shows the performance of a regulator with a gain of 5 with load disturbances. There are large steady-state errors as expected. Notice the sensitivity to the load disturbances. Figure 4 shows the response when a PI regulator is used. A comparison of Figs. 3 and 4 clearly shows the benefit of integral action in reducing steady-state errors. The PI regulator has a gain of 10 and an integral time of 8 sec.

It is 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 a gain of 5.

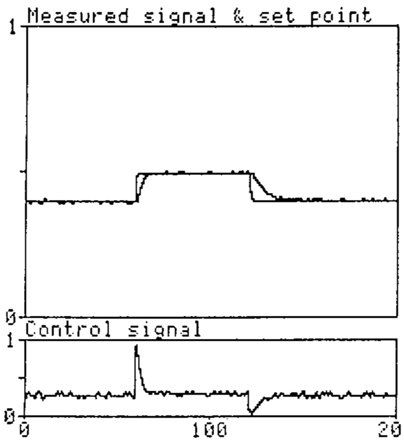

Fig. 4. Results of level control of the upper tank with a PI regulator. Note that there are no steady-state errors.

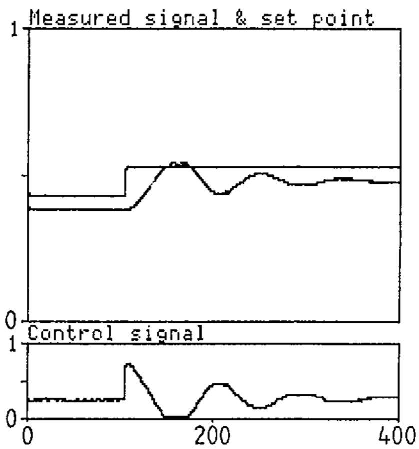

Fig. 5. Results of level control of the lower tank by a proportional regulator. Note the large steady-state error.

Integral action eliminates the steady-state errors. However, a PI regulator gives a poorly damped closed-loop system, and, therefore, it is necessary to introduce derivation action to provide reasonable damping. The students discover these facts empirically by experimentation. Because of the intentionally long time constants they will also become impatient when experimenting with the lower tank. This motivates analysis and use of rational tuning procedures.

In summary, the first experiment serves to familiarize the students with simple feedback loops and the characteristics of P, PI, and PID control. They should also become familiar with the 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. The students also notice that some systems, e.g., the upper tank, are easy to control, while others, e.g., the lower tank, are more difficult. The highest loop gain is determined by the measurement noise and actuator saturation when controlling the upper tank. It is limited by process dynamics when controlling the lower tank.

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

$$\frac{dh_1}{dt} = -\alpha_1(2gh_1)^{1/2} + \beta u$$

$$\frac{dh_2}{dt} = \alpha_1(2gh_1)^{1/2} - \alpha_2(2gh_1)^{1/2}$$

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

$$\beta = k_m/A$$

where k_m is a 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 slightly 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_0. 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 and h_l. There are menu-driven programs that assist in determining the parameters.

Linearized Models The linearized process dynamics can be described by the following 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

$$T_i = A/a_i(2h_i^0/g)^{1/2}, \qquad i = 1, 2 \text{ [sec]}$$

$$k_p = k_m k_c/A \text{ [sec}^{-1}]$$

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

The linear models will be valid as long as there is no overflow and 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 straightforward to carry out the control design. Since the dynamics of the upper tank is described by 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. However, a high value of ω will give a high gain. In the first experiment, it was found empirically that the gain was, in fact, limited by the measurement noise. Thus, in practice, this will limit the achievable bandwidth.

In the first experiment, the students experienced some difficulties in controlling the level of the lower tank with a PI regulator. They found that derivative action was needed to improve system damping. To make a systematic design of a PID regulator to control the lower tank, it is first observed that the process dynamics is of second order. The closed-loop system obtained with PID control is thus of third order. The parameters of the regulator can be determined by pole-placement design. The desired closed-loop polynomial is specified as

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

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 students calculate the 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 ballpark with considerably 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 much more oscillatory than those obtained by the more elaborate pole-placement method.

Summary The message of this experiment is that it is straightforward to obtain good regulators if a process model 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 introduce 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 small amount of 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 [6].

Another point that we emphasize is the usefulness of a digital computer in other than pure control tasks. Inclusion of design calculations in the regulator code is a typical example. Another step we can take 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 the consequences of different choices of pole placement. They are also requested to investigate the sensitivity to modeling errors by introducing incorrect data for the process parameters.

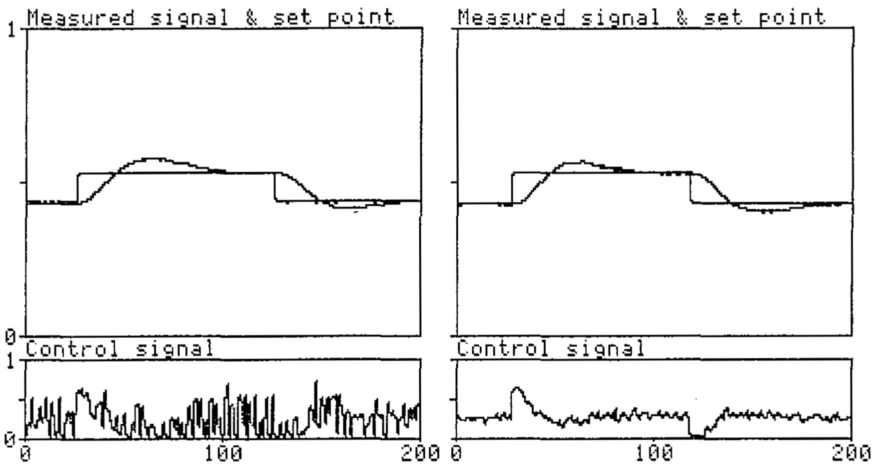

Fig. 7. PID control of the lower tank. The maximum derivative gain is 50 in the curves to the left and 5 in the curves to the right.

The phenomena of integrator windup are also illustrated. See Fig. 6. How to avoid windup by back calculation is discussed in detail. The experiment shown in Fig. 6 is a good demonstration of the benefits of having compensation for windup in a regulator.

Program PIDS2 is used for PID control of a general second-order system. This program accepts a second-order process model and specifications in terms of ω, ζ, and α. The program performs the design calculations and executes the PID control and the graphics. This program is used to perform experiments with level control of the lower tank. The experiments performed include investigation of the sensitivity to model errors and the effects of the sampling rate.

The details of the digital implementation of a PID algorithm are discussed, including limitation of the high-frequency derivative gain. This means that the ideal derivative sT_d is replaced by

$$sT_d \approx \frac{sT_d}{1 + sT_d/N}$$

where N is the maximum derivative gain. Experiments are performed to show the effects of different values of N. Some results are shown in Fig. 7. Note that the controlled variables are virtually the same, but the control signals are drastically different. The necessity to have backward differences when approximating the derivative part is demonstrated. The choice of sampling rates is also conveniently explored by using 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 used to tune the parameters of a PID controller, see [7]. The students 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 is very simple on the Apple II because it has memory-mapped I/O. The students are requested to write a small Basic program for control.

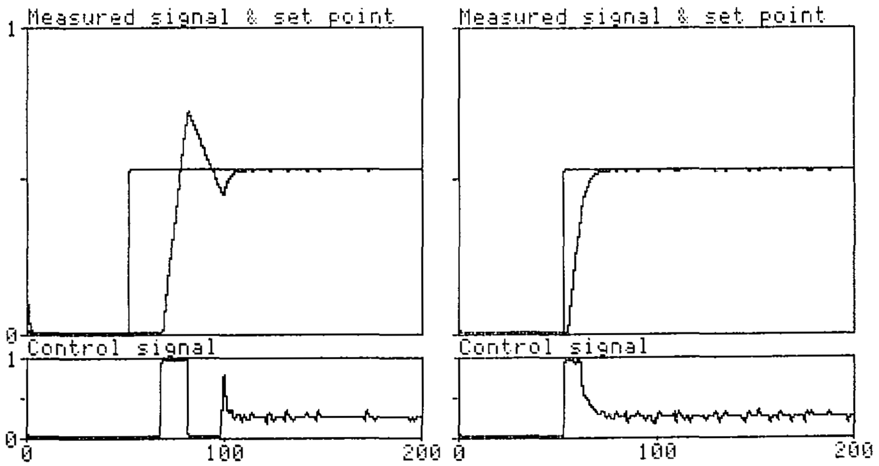

Fig. 6. Integral windup in level control of the upper tank with a PI regulator (left). Illustration of the dramatic improvement obtained with a regulator with compensation for windup (right).

Experiment 4

The purpose of the final experiment is to illustrate state feedback, Kalman filtering, and output feedback via a combination of state feedback and Kalman filtering. The experiments are carried out using 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

$$u(t) = l_1(\gamma r - h_1) + l_2\{(r - h_2) + 1/T \int (r - h_2)\, ds\}$$

The reference value is r. The term γr represents a feed-forward compensation. 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 such 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. A comparison of Figs. 7 and 8 shows that the performance with state feedback is slightly better than with PID control. The difference is particularly noticeable in the control signal. The reason is, of course, that it is better to measure the state directly than to try to recover it by differentiation.

Selectors When the level of the lower tank is controlled by PID control from lower level measurements, 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. For this reason, a minimum selector is introduced in the algorithm. The selector simply measures the deviation of the level in the upper tank from the flooding level. It switches to upper tank level control when the level in the upper tank becomes too high.

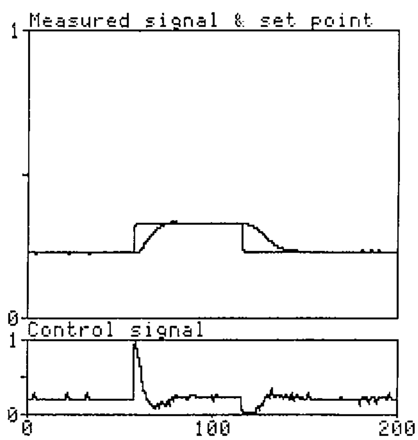

Fig. 8. Results of level control of the lower tank by state feedback.

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 such 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 are nonlinear, the Kalman-filter-based linear approximation is valid only in a region around the linearization point. The properties of the Kalman filter are illustrated in Fig. 9, which shows the input signal u, the estimated level, and the true measured level in the upper tank.

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 results obtained are illustrated in Fig. 10. They can be compared with the corresponding results with PID control in Fig. 7 and with the results from state feedback with an extra sensor in Fig. 8. The Kalman filter gives a slight deterioration as compared to a direct measurement of the state. This appears as variations in the control signal. The responses

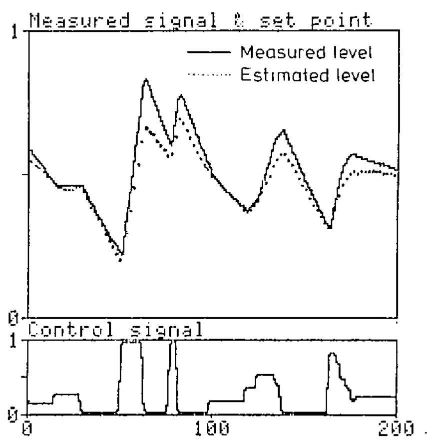

Fig. 9. Results of estimation of the level in the upper tank based on measurement of the lower tank level using a Kalman filter.

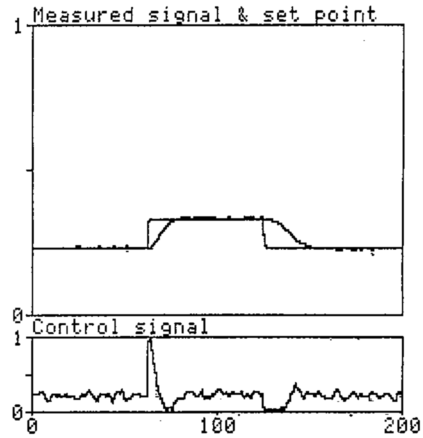

Fig. 10. Results of level control of the lower tank based on measurement of the lower tank level only. The regulator is based on state feedback and Kalman filtering.

of the controlled output to command signals in Figs. 8 and 10 are almost identical. The regulator based on state feedback and Kalman filtering is slightly better than the PID regulator because it rejects measurement noise better.

Experiences

The laboratory is coordinated by a supervisory assistant, who prepares the lab, supervises the other assistants, draws up time schedules, and makes sure that there is an assistant for each laboratory session. The time schedule is available to the students two weeks before the start of the experiments. The laboratory presently allows 15 sessions per week, which corresponds to a capacity of 240 students per week. Thirteen sessions per week have actually been run.

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

The students have their own 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 that includes all the experiments. The students then have all their notes and results available in one place for easy reference in subsequent experiments and for problem-solving sessions.

The students are required to prepare for the experiments. This demands coordination between lectures, problem-solving sessions, and the laboratory experiments. For example, to prepare for the second experiment, the students have to make a mathematical model of two cascaded tanks and linearize them. The preparations also include a review of relevant theory and earlier experiments.

Each laboratory session begins with a quiz on the assigned homework. The assistant varies problems from time to time. The problems cover theoretical material related to the experiment. The assistant selects two problems for the test, e.g., to draw a Bode diagram from a given transfer function or to linearize a given equation. To avoid unnecessary use of valuable time, the assistant checks homework during testing. Students who are not properly prepared are sent home. It is quite important that the students be properly prepared, otherwise they will not get the message and they will take too much valuable time from the other students. Experience has shown that a stern policy on sending home unprepared students at the beginning of sessions seems to yield immediate results in the quality of the preparations in future sessions.

After the quiz, a short introduction is given in the form of a slide show to summarize the goals and the exercises of the experiment.

Students are exposed to working with practical control problems in the laboratory. We have found it favorable to have them work in pairs. This helps in double-checking calculations, numbers, etc., which is so essential in practical work. It also promotes discussions.

Since the setups are easy to handle, the assistant does not have to spend time explaining the equipment. Instead, the valuable time can be used to discuss the exercises and problems with the students and to check that they do the experiments carefully and make proper notes.

Conclusions

We have had very good experiences with 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 not covered in ordinary courses. The lab has been very well received by many different student categories. The fact that the dynamics are essentially self-explanatory is an important factor. The availability of good teaching material has been critical to teaching efficiently.

Acknowledgments

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Karl Johan Åström is Professor of the Chair of Automatic Control at Lund University. He was educated at the Royal Institute of Technology in Stockholm, Sweden, and has worked for IBM. Professor Åström is a Fellow of the IEEE and a member of the IFAC Council. He is interested in many aspects of automatic control.

Ann-Britt Östberg earned the M.S. degree in engineering science at the Lund Institute of Technology in 1976. After graduation, she joined the Department of Automatic Control as a Research Engineer working on teaching and research projects. In 1986, she joined Sydkraft AB Malmö, where she currently is employed as a Control Engineer.