Lund Control Program Combines Theory with Hands-On Experience

Åström, Karl Johan; Lundh, Michael

Published in:
IEEE Control Systems

1992

Citation for published version (APA):
Åström, K. J., & Lundh, M. (1992). Lund Control Program Combines Theory with Hands-On Experience. *IEEE Control Systems*, *12*(3), 22-30.

Total number of authors:
2

Lund Control Program Combines Theory with Hands-On Experience

K. J. Åström and M. Lundh

A major goal of the control laboratory and curriculum at Lund Institute of Technology in Sweden is to give students a strong background in control theory and an engineering ability to make control systems that work. This is accomplished with a coordinated course structure that is applicable to undergraduates, graduates, and continuing education. The program's control laboratory utilizes a variety of software packages that cover simulation, indentification, control design, and on-line computer control.

Automatic Control Education

Automatic control is a relatively recent contribution to engineering science that emerged as a discipline in the 1950s. To give a perspective it can be mentioned that the Servomechanism Laboratory at M.I.T. celebrated its 50 year anniversary in 1990 and that the October 1990 issue of the journal *Control Engineering* was devoted to a 50 year jubilee of process control. Methodology and technology have developed rapidly during this period. A very attractive feature of feedback control is its generality and its wide application area. However, this feature also creates difficulties in teaching the engineering aspects of the field.

Engineering education in Sweden has always been executed in separated Institutes of Technology (tekniska högskolor) following the pattern of Continental Europe. The number of students accepted is determined centrally by the Ministry of Education. Admission and allocation of students to different universities is done centrally for the whole country based on high school grades. The quality of the students is quite good. Currently there are five Institutes of Technology in Sweden. The schools have the traditional disciplines of civil engineering, mechanical engineering, electrical engineering, chemical engineering, and computer engineering. There is also a discipline of engineering physics, which is an engineering education with a strong science emphasis. More specialized branches like mining and aeronautical engineering are only available at some institutes. The curriculum is based on a 4.5 year program leading to a degree called civ. ing. (civilingenjör), which is roughly equivalent to an M.S. degree. The education has a good status. It is the major source of engineers for industry, and the majority of the students will work in industry after graduation. In a small country it is important that engineers are given a balanced education so that they can adapt to a wide variety of industrial needs.

Automatic control has been part of engineering education since the mid-1960s. At Lund, control education is centralized with one department responsible for all control courses given to students in engineering physics, electrical engineering, computer engineering, mechanical engineering and chemical engineering [1],[2]. Control courses started in 1965. The department has two professors and four associate professors.

A major goal of our education in automatic control is to give students a strong background in control theory and an engineering ability to make control systems that work. At Lund such a goal seems to be in harmony with industrial demands on education [3]. Laboratory experiments are essential to reach this goal. The time available for experiments in undergraduate courses is very restricted, typically four hours for an experiment. It is therefore essential to focus on the essentials and avoid tedious hand calculations and programming. The experiments focus on control engineering issues and the experiments are designed so that the time from specifications to a running closed loop system is short.

Course Structure

Different aspects on course structure and curricula are found in [4]-[10]. In the Control Department there are three types of courses given, courses for the engineering program, Ph.D. courses, and continuing education courses for engineers in industry.

Engineering Courses

All engineers except civil engineers take an introductory course which covers feedback control from state space and frequency response points of view. This is a typical undergraduate course which is given in the first semester in the third year. The textbook used is [11]. There are three different courses: one in engineering physics, electrical engineering and computer engineering, another to mechanical engineering students, and a third one to chemical engineering students. These courses cover essentially the same material but have a difference in pedagogy. Electrical engineering students are quite accustomed to abstract thinking; they have also had a course in linear systems. For these students the material is presented top down, i.e., the theory is first developed in a concise manner and the engineering aspects are then introduced. Students in mechanical and chemical engineering are not so used to abstract thinking. The courses for these students are therefore taught bottom up starting with specific technical problems and introducing mathematics gradually as needed. The classes are quite large. The course for electrical engineers has about 280 students and the courses for mechanical and chemical engineering have about 100 students each.

There are three types of teaching: lectures to all students, problem solving sessions in groups of 20-30 students, and laboratory experiments in groups of 8-16 students. There is strong coordination between the different teaching modes. Four canned laboratory experiments are made in the introductory courses, they are: 1) empirical investigation of PID controllers, 2) modeling and simple control design, 3) state feedback and observers, and 4) control design using MATLAB. By arranging the laboratory experiments so that all students in a course

---

Based on a paper presented at the 1991 American Control Conference, Boston, MA, June 26-28, 1991. The authors are with the Department of Automatic Control, Lund Institute of Technology, P. O. Box 118, S-2217 00 Lund, Sweden.

0272-1708/92/$03.00©1992IEEE

can make an experiment in less than 2 weeks it is possible also to integrate the laboratories. In the third week of the course all students thus have empirical experience of a simple feedback system with PID control. They have seen effects of load disturbances, measurement noise, actuator saturation and windup.

The introductory course is typically taken in the fall of the third year. After that, students can select a number of elective advanced courses: digital control, adaptive control, system identification, and computer implementation of control systems. The number of students in these courses ranges from 20 to 100. The courses on digital control and computer implementation correspond to undergraduate courses. The other are equivalent to first year graduate courses. The textbooks used for the courses on digital and adaptive control are [12] and [13]. Lecture notes are used for the other courses. Laboratory experiments and projects are an integral part of the courses. In courses with a small number of students it is possible to provide team and communication skills. For example, in the course on computer implementation of control systems the students are split into teams that solve parts of a problem with well defined interfaces. The software written by different teams should be able to function together to perform the specified tasks.

Our policy is that the courses are the responsibility of the department and not of an individual faculty member. Several measures are taken to ensure that the contents of the course are the same irrespective of who teaches it. A complete file of viewgraphs are maintained to document the courses even if the blackboard is mostly used. An extensive problem book with complete solutions is used for the problem solving sessions. Documents for students and instructors for laboratory sessions are provided.

Over the years we have also worked with the other departments to integrate the curriculum. Some old courses in the mathematics department on ordinary differential equations and transforms have been combined into a linear systems course, which is taken by all students in in engineering physics, electrical engineering, and computer engineering. We have also other departments at our university that use MATLAB.

Courses at Swedish universities are traditionally taught in Swedish. To make international cooperation easier we write several textbooks in English, [12]-[14]. For a long time we have given certain graduate courses in English. Recently it has also been possible to give other courses in English.

Ph.D. Courses

There is a Ph.D. program at the department. The program is nominally 4 years, split evenly between courses and a thesis. Students who are also working at the department are expected to finish in five years. About two students per year are accepted into the program, and occasionally there are also some students from industry. The following courses are offered in the Ph.D. program: linear systems, stochastic control theory, nonlinear systems, optimal control, control system design, modeling, identification, adaptive control, real-time programming, and process control. Our Ph.D. students also take courses from many other departments such as mathematics and computer science. Our Ph.D. courses are also taken by students from other departments.

Continuing Education

Prior to 1980, continuing education was traditionally performed by engineering organizations and several department members were engaged in this. Around 1980 the universities were charged with this task too. Continuing education provides many interesting opportunities. The courses give good contact with practicing engineers and their needs. The courses offer a good opportunity for technology transfer from research to engineering practice and they make experimenting with different courses a possibility. At the moment we have a format with courses lasting from three to five days. They are all given at the university so that we can use our laboratory and computer facilities. Typically we give three to four courses per year, the number of participants is limited to 24 to make sure that there is good interaction. Examples of courses are: Introduction to Feedback Control, System Identification, Adaptive Control, Computer Aided Control Engineering, Simulation, Process Control, and Engineering applications of AI.

Thesis Projects

All students must complete a thesis project to obtain their engineering degree. The students can select their area of specialization. About 20-30 students per year do their thesis project in the field of automatic control. The projects are of different types. They can arise from our current research projects, they can be small experimental projects in our laboratory, or they can be industrial projects.

The Control Laboratory

One difficulty in teaching automatic control is to provide a balance between theory and practice. A control laboratory is an indispensable tool to provide this. There are many different requirements on a laboratory. In our case it is necessary to have a large number of identical experiments for the large classes in the introductory courses as well as specialized individual experiments for courses and projects. Many papers have been written on control laboratories. See, for instance, [15]-[22].

A key idea of our laboratory is that it should illustrate all aspects of control engineering, i.e., modeling, identification, simulation, analysis, design, and implementation. Twenty years ago it was necessary to use specialized equipment to cover these tasks. The availability of microprocessors and personal computers has made it much simpler to develop cheap and reliable laboratory processes. A personal computer can be used to implement the control algorithm, for graphics and for computer aided design and instruction. The only specialized equipment that is used is a good frequency response analyzer for easy determination of frequency responses. This instrument is interfaced to a personal computer to simplify its use. We also have a number of standard controllers and a small distributed control system.

Desktop Processes

A number of small pilot plants that fit on a desktop next to a personal computer have been developed. It is no simple task to develop good processes and experiments. According to [15] a good laboratory experiment should demonstrate important theoretical ideas, reflect important real life problems, give visual and acoustic sensation, have a suitable time scale, be nonhazardous, be inexpensive, and be easy to understand and use. Due to large classes we have extreme requirements for the reliability of the equipment. During peak loads more than 250 students may do laboratory experiments in one week. We have made many attempts to use commercially available laboratory processes, but we have been quite disappointed both with respect to reliability and ergonomics. The following desk top processes are currently in use: double tank, simple

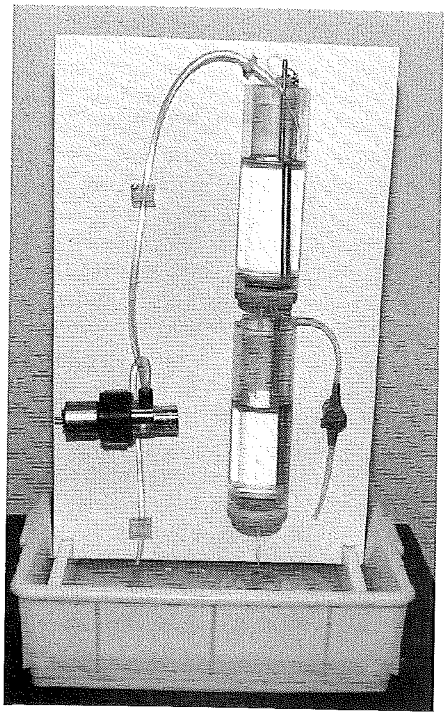


Fig. 1. The double tank.

servo, flexible servo, ball and beam, fan and plate, and an automated tea kettle. The first three processes are standard equipment that are found in most control laboratories. They have been designed and built at the department. The double tank process and the simple servo are used in the introductory courses. The double tank and the experiments made are described in [23]. Fig. 1 shows the process. The servo is a simple motor drive with motor, gear, tachometer, shaft encoder. See Fig. 2. The system is made in such a way that it is easy to modify by introducing compliance and backlash. There are facilities for simple analog feedback as well as simple computer interfaces. The properties of proportional and velocity feedback can be demonstrated simply by connecting wires on the front panel. A torque disturbance on the motor shaft may be activated by a switch to simulate load disturbances. Several versions of the servo with compliance are used. The servos are the standard equipment in the digital control course.

The ball and beam is a servo-controlled tilting track with a ball rolling in the track (Fig. 3). The motors used are strong enough to throw the ball. The fan and plate (Fig. 4) is described in [24]. The automated tea kettle is used to teach logic and sequencing. The same components are used in several different processes, which simplifies maintenance and reduces costs. A general motor drive is used for all servos. Many identical processes are used in the introductory courses. Several other processes are used in multiples of four units.

A number of special more complicated processes are also used, e.g., copper rod with peltier effect elements, concentration control system, inverted pendulum on an hydraulic servo, a discrete manufacturing system in lego, a mobile vehicle with ilon wheel, and an industrial robot. These processes are mostly used in projects and in thesis work.

Computing Facilities

The major computing facility at the department is a network of Sun workstations connected to servers and the university network by ethernet. Currently we have about 30 Sparc stations with servers. The software that is mostly used are Simnon, a simulator for nonlinear systems and MATLAB with toolboxes.

IBM PC AT with EGA graphics is the standard computer used for simple laboratory experiments. All systems have AD and DA converters. They are provided with MATLAB and Simnon for computations and simulations. Real time programming is currently done in Modula-2. We have a very convenient way to move from simulation to on-line control. A real time version of Simnon admits processes to be connected to the computer via AD and DA converters

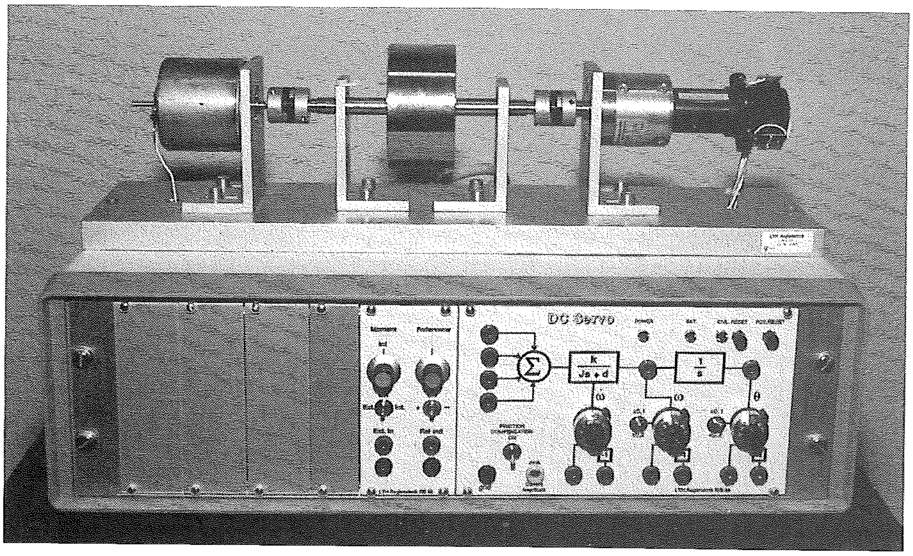


Fig. 2. A simple servomechanism.

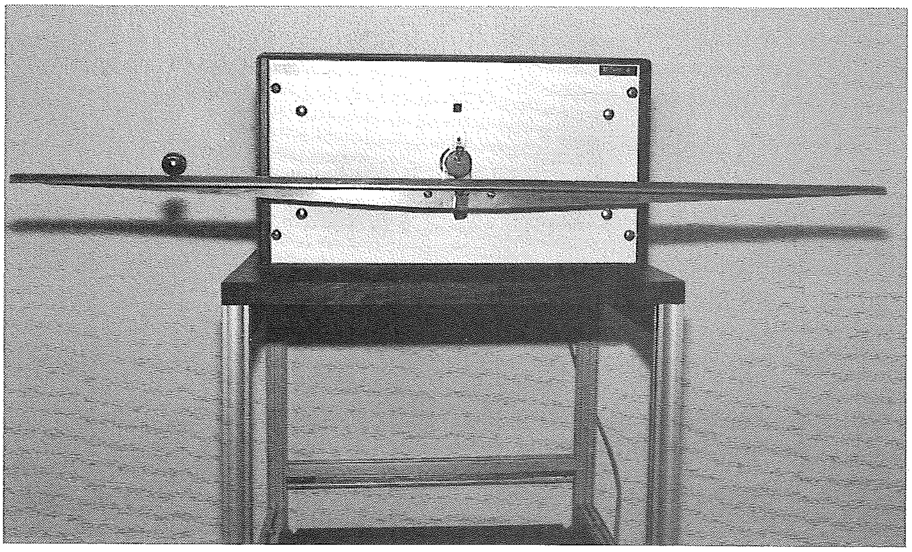


Fig. 3. The ball and beam.

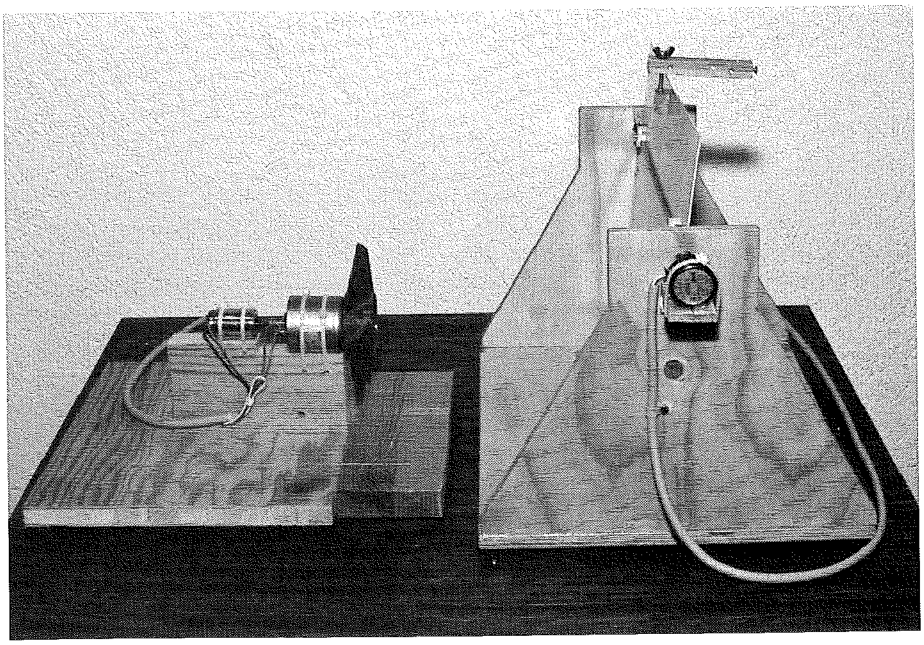


Fig. 4. Fan and plate process.

[25]. We also have a program that automatically translates Simnon code to Modula-2 with calls to a real time kernel. See [26]. In this way it is easy to start with a pure Simnon simulation, then control the process via the simulator on the PC and finally to control the process using a proper real time program. The real-time version of Simnon can also be used to implement virtual processes, i.e., a box with AD and DA converters that contain a high fidelity simulation of a complex process.

The program for automatic translation of Simnon code for Modula-2 has been used to develop several of the systems used in our canned teaching experiments. Availability of software of this type simplifies maintenance of software significantly. Fig. 5 shows the configuration of the stand alone systems used.

For more ambitious experimentation we are using Motorola 680X0 processors and signal processors on a VME bus. The systems are connected to the computer net with Sun workstations. This means that a process connected to the network can be viewed as a Labserver and accesses remotely as laser printers or other peripheral devices. Interface routines that make it easy to get experimental data to MATLAB in real time are also available. The architecture of our computer system is shown in Fig. 6.

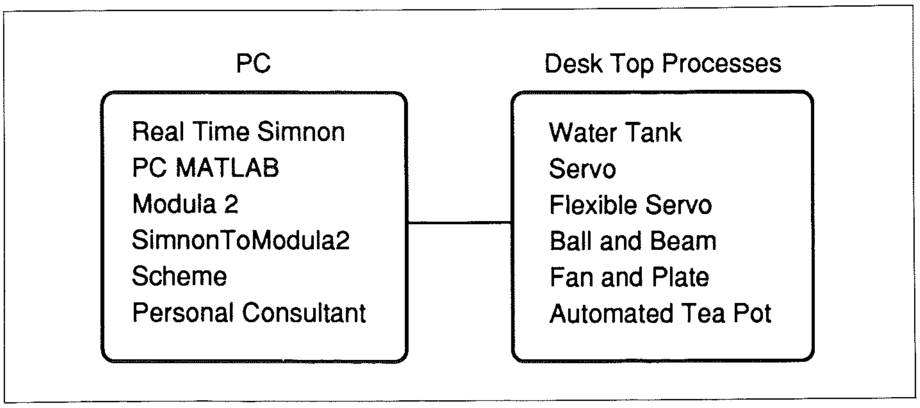


Fig. 5. Configuration of the stand alone systems for laboratory experiments.

The Creativity Laboratory

The laboratory experiments in the introductory course are highly structured. The labs are less structured in the elective courses. Some of these courses also have a one week project. The ordinary processes are used for this purpose but the tasks given are more open ended. One vehicle for these more open ended experiments is the Creativity Laboratory. The idea with this laboratory is to have a facility where students can put control systems together from scratch with a modest effort. The laboratory processes are the same as in the other labs. Macintosh computers are used. A simple AppleTalk interface for the VME bus systems has been developed. The Macintosh computers are provided with LabView. One machine also has a DSP card with a TMS320C on the Nubus to provide fast computation.

Computer Aided Control Engineering (CACE)

Computer aided engineering tools are an important aspect of teaching, since they make it possible to significantly increase the personal efficiency in problem solving. They also make it possible to deal with realistic problems, which contributes to making teaching more interesting and more realistic. Different aspects of CACE are found in [16] and [27]-[35]. The efforts by Schaufelberger are particularly innovative and noteworthy. Since no tools were available in the beginning of the seventies we developed our own tools for modeling, analysis and simulation, control design, and implementation. See [27]. When commercial tools became available we started to use them. Currently our standard tools are MATLAB [36] for calculations and design and Simnon [25] for simulation. These tools have been integrated so that it is easy to transfer data files between the systems. Software to convert linear system descriptions in MATLAB to Simnon systems have also been developed. As mentioned in the previous section, we have a version of Simnon that admits connection to the real world via AD and DA converters. For symbolic calculations we use Maple and Mathematica.

Textbooks like [13] and [12] have made extensive use of simulation to illustrate system behavior. All graphs in the books are documented as Simnon macros. We have had very good experiences from providing students with the macros. Students can learn much by exploring the system experimentally by simulation.

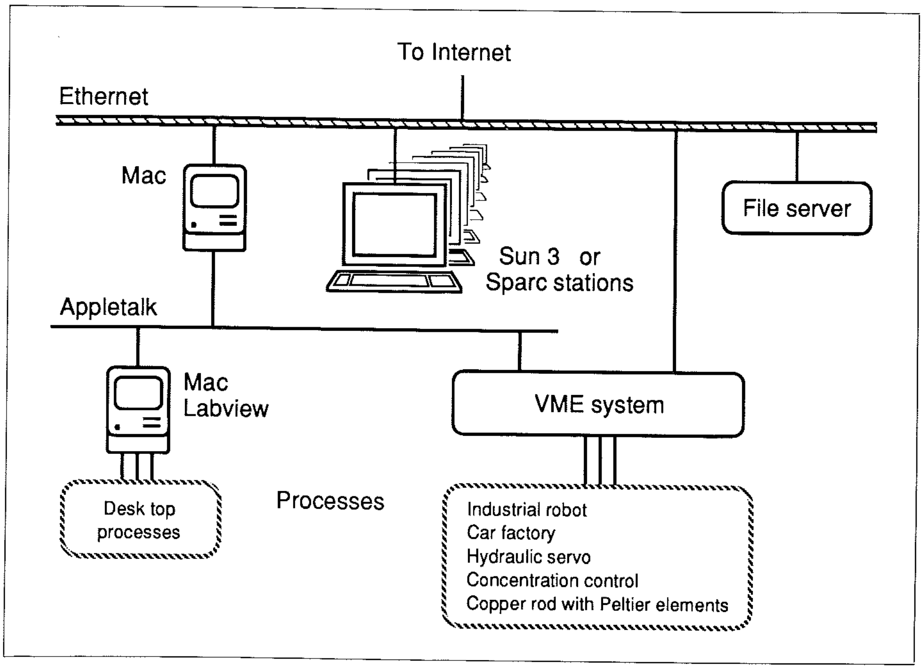


Fig. 6. Architecture of the computer system.

Several toolboxes for education have also been developed, e.g. [37]. Special programs for laboratory experiments have been written in Modula-2 (see [38]). We have also developed special teaching programs. One example is a program called VISIDYN [39]. Its purpose is to make it easy to explore relations between different representations of linear systems like pole-zero plots, Bode diagrams, step responses. The program is inspired by the spread sheet paradigm. Each representation is presented graphically in a window. The representations can be manipulated directly with the relations between the representations being maintained automatically. The program shows both open and closed loop properties.

The experiences from using CACE tools have been excellent. From a pedagogical point of view it would however be extremely useful to have one environment that admits matrix computations, computer algebra and simulation with simple interfaces to real processes.

Laboratory Staff

Maintaining a control laboratory requires resources. It is necessary to have a qualified support staff to help developing, running and maintaining the laboratory. In our case we have a laboratory staff consisting of four persons, one manager with wide skills, one electronics engineer and two software engineers. The laboratory staff is also responsible for all computers and work stations. They also participate in our research projects. Supervising laboratory experiments is also a natural way for the Ph.D. students to practice their engineering ability to make systems work. The availability of a skilled laboratory staff is a very valuable asset and a necessity to reach the educational goals on engineering ability. The laboratory staff also makes it possible to maintain the expertise required to interface computers to industrial processes and to make experiments and feasibility studies in industry. This has been very beneficial for our research and for the transfer of ideas to real industrial use.

A Software Package for On-Line Control

Many of the laboratory processes and tools are used in many different courses. To illustrate this we will describe software used for on-line experiments in the courses on digital and adaptive control. The software implements a digital controller with anti-windup protection. The system also contains software for control design and parameter estimation. Many task can be performed with the system.

The software runs on an IBM PC/AT or a compatible machine. It is used to control the desktop processes. The system has been used for courses in digital and adaptive control since 1987. So far it has been used by more than 600 students. The system has also been used extensively in demonstrations and projects. More details about the system are given in [38].

Controller

The controller is a multiple-input single-output system which is described by

$$R(q)u(k) = T(q)r(k) - S_1(q)y_1(k) - S_2(q)y_2(k) - S_3(q)y_3(k) \qquad (1)$$

where u is the control signal, r the reference signal and y_i are feedback signals that are read from AD-converters. Furthermore R, T, S_1, S_2 and S_3 are polynomials of degree $n \leq 5$ in the forward shift operator q.

Equation (1) describes the small-signal behavior of the controller. To avoid windup the controller is actually given by:

$$A_o(q)v(k) = T(q)r(k) - S_1(q)y_1(k) - S_2(q)y_2(k) - S_3(q)y_3(k) + (A_o(q) - R(q))u(k) \qquad (2)$$

$$u(k) = \begin{cases} u_{low}, & \text{if } v(k) < u_{low} \\ u_{high}, & \text{if } v(k) > u_{high} \\ v(k), & \text{otherwise.} \end{cases}$$

(see [12]). The polynomial $A_o(q)$ can be interpreted as an observer polynomial. When the control signal does not saturate (2) is equivalent to (1).

The reference signal r can either be an external signal, it can be read from an AD-converter or it can be generated internally from a signal generator in the program. The available signals are square wave, triangle wave, sine wave, a step or a ramp. The mean value and the amplitude can also be selected.

Control Design

A control design method based on pole placement is included in the program. The method will be described briefly, more details are given in [12]. The polynomials $R(q)$, $S_1(q)$, and $T(q)$ in (1) are determined from specifications on the closed loop system.

It is assumed that the process model is described as a rational pulse transfer function

$$H(q) = \frac{B(q)}{A(q)} = \frac{B^+(q)B^-(q)}{A(q)} \qquad (3)$$

where the numerator polynomial $B(q)$ has been factored in one part $B^+(q)$ that is cancelled by the controller, and one part $B^-(q)$ that remains in the closed loop transfer function.

The specifications are given in terms of the closed loop polynomials A_m and A_o. These polynomials may be given in continuous time. The program will automatically calculate the discrete time equivalents. The desired closed loop system from reference r to output y_1 is

$$H_m(q) = \frac{B_m(q)}{A_m(q)} = \frac{B_m'(q)B^-(q)}{A_m(q)}$$

It can be specified that the controller has integral action by requiring that polynomial R has $A_r(q) = q - 1$ as a factor. The controller is obtained by solving

$$A(q)A_r(q)R'(q) + B^-(q)S_1(q) = A_m(q)A_o(q) \qquad (5)$$

for $R'(q)$ and $S_1(q)$. This equation is solved by inverting the associated Sylvester matrix. The polynomials in the controller (2) are then given by $S_1(q)$ in (5) and

$$\begin{aligned} R(q) &= B^+(q)A_r(q)R'(q) \\ T(q) &= B_m'(q)A_o(q) \end{aligned} \qquad (6)$$

System Identification

The program has facilities for system identification. A process model

$$y(k) = \frac{B(q)}{q^d A(q)} u(k)$$

is estimated. The total number of unknown parameters in polynomials A and B is less than 10 and the delay d ranges from 0 to 3. A square root algorithm for recursive least-squares identification is implemented as described in [13]. This algorithm is a scaled version of Biermann's Choleski-factorization [40], where the covariance matrix is factored as $P(k) = L(k)D(k)L^T(k)$. The left triangular matrix L, with ones on the diagonal, and the diagonal matrix D are updated separately. The parameter estimator can be tuned by choosing the initial covariance matrix $P(0)$, the forgetting factor λ and a second order regression filter $B_f(q)/A_f(q)$.

Man-Machine Interface

A simple interface is provided to communicate with the program. Data is entered using mouse and keyboard. Signals and parameters are displayed on the screen using EGA graphics. Signals can be plotted in real time. The reference signal r and the plant output y_1 are always displayed. The signals y_2, y_3, u and the control error $r-y_1$ can be shown on demand. The man-machine interface is organized in seven different menus. These are:

SETUP	Set parameters describing I/O-channels, control signal limits, axis scales etc.
MODEL	Specification and analysis of the process model. A Bode plot of the process model and the loop transfer function can be shown. The evolution of the parameters of the estimated model can also be displayed, but not in real time.
DESIGN	Menu for entering specifications for the pole placement design. Different menus are used for fixed and adaptive controllers.
REGUL	Menu for direct specification of controller polynomials. Polynomials r, S_1, S_2, S_3, and T can be set.
REFSIG	Selection of reference signal.
PLOT	For full screen plots in real time. The signals r, y_i, u and $r-y_1$ may be shown.
ESTIM	Set and display variables of the recursive parameter estimator. The evolution of the diagonal matrix D in the factorization of the covariance matrix P may also be displayed, however, not in real time.

A small plot window is present on all menus with the exception of the PLOT-menu. The reference signal r and the process output y_1 are plotted in real time in this window. Any design procedure written in MATLAB can be used to design the controller. The controller polynomials in (2) and the sampling interval (TS) are then be written on a MATLAB-script file (file.m) with

```
>> poly2tbx('file',TS,R,S1,S2,S3,T,AO)
```

This file may be read by the program to introduce controller parameters.

Implementation

The program is written in Modula-2. It uses a real time kernel and a graphics library. Excluding the libraries the source code consists of 5800 lines. The program has six concurrent processes. One is executed periodically using the real time clock and the others are waiting for different events.

With a slow IBM AT having an 8 MHz 80286 processor and an 80287 numeric co-processor, a second order controller with constant parameters can be run at 50 Hz, this also includes real time plotting. The sampling time is slowed down to 25 Hz if in addition four parameters are estimated. An indirect adaptive controller that estimates four parameters and determines a new controller every sample can be run at 10 Hz.

Examples

The system can be used in many different ways. Two examples, taken from courses in digital control and adaptive control, demonstrate the ideas. Position control of the DC-servo in Fig. 2 is used as an illustration. The continuous time transfer function from control signal to angle is

$$G(s) = \frac{11.2}{s(s+0.12)} \qquad (8)$$

The corresponding discrete time transfer function is

$$H(q) = \frac{B(q)}{A(q)} = \frac{b_1 q + b_2}{q^2 + a_1 q + a_2} \qquad (9)$$

where the coefficients depend on the sampling interval.

Example 1 — Digital Control

The first example illustrates how the system may be used to design a digital controller. A key issue is to show how the properties of the closed loop system is influenced by different pole locations and how the performance is constrained by measurement noise and model mismatch.

Sampling of (8) with period $t_s = 0.10$ s gives a discrete time model (9) with

$$\begin{aligned} B(q) &= 0.558q + 0.0556 \\ A(q) &= q^2 - 1.9881q + 0.9981 \end{aligned}$$

The polynomial $B(q)$ has a zero at $q = -0.996$. Such a zero should not be canceled by the controller. Therefore we choose $B^-(q) = B(q)$. The desired closed-loop poles are given in terms of the continuous time characteristic polynomial

$$s^2 + 2\zeta\omega s + \omega^2 \qquad (10)$$

The discrete time counterpart is then obtained using the sampling interval. Choosing $\omega_m = 7$ and $\zeta_m = 0.7$ in (10) gives

$$A_m(q) = q^2 - 1.0753q + 0.3753$$

Similarly $\omega_o = 9$ and $\zeta_o = 0.8$ in (10) gives

$$A_o(q) = q^2 - 0.8350q + 0.2369$$

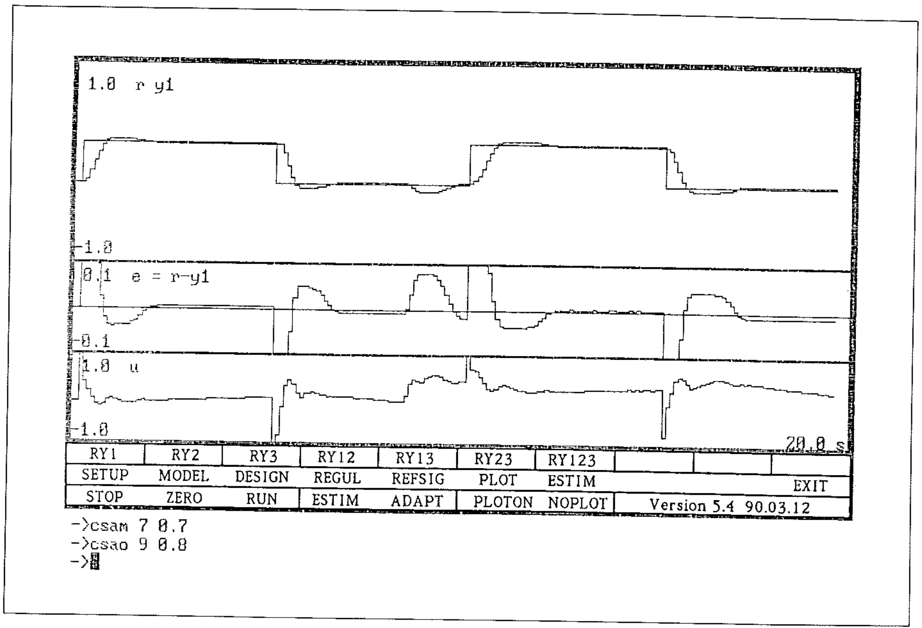
To do this the student has entered t_s, ω_m, ζ_m, ω_o, and ζ_o using the keyboard. Three commands were also given using the mouse: The process (8) was sampled to give (9), a controller with integral action was chosen, and the controller polynomials were calculated from (5) and (6). Two more commands given by the mouse starts the controller and selects the PLOT-menu.

Fig. 7 shows the screen for the PLOT-menu after 20 s of operation. The reference signal r and the output signal y_1 are plotted in the upper window. In the middle window the difference between them $e = r - y_1$ is plotted in another scale. The lower window is for control signal (u) plots. A torque disturbance is introduced at time $t \approx 8$ s.

Changing menu to the DESIGN-menu allows specifications to be changed and new controller polynomials to be computed and transferred to the controller while this is running.

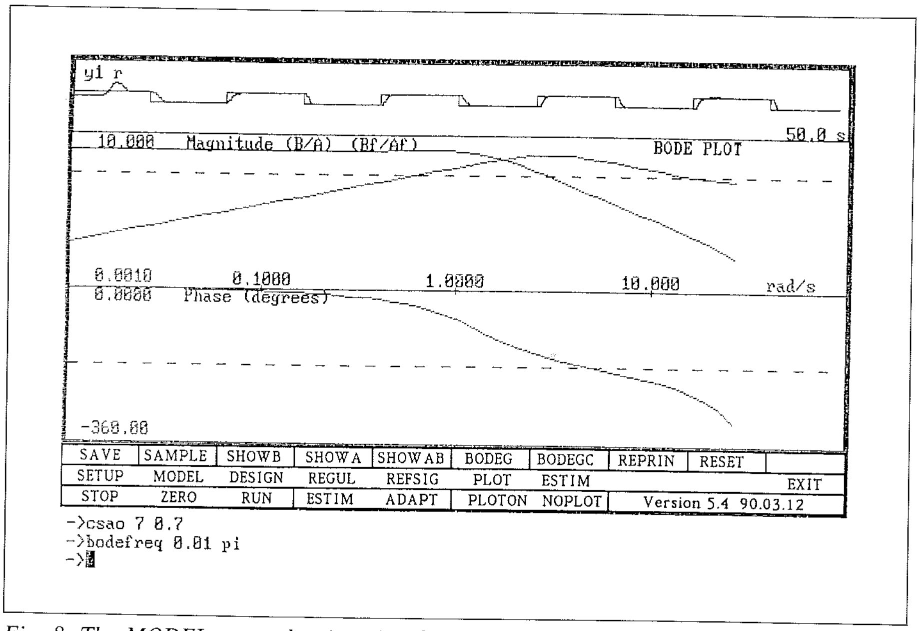
The example clearly illustrates that only a few simple actions are required to change specifications and have a new controller running. Because of this a student can get a good intuitive feel of control design. The system is very flexible. Since the system contains both control design and parameter estimation it is straight forward to configure an adaptive controller. This is illustrated in the next example.

Example 2 — Adaptive Control



```
->csam 7 0.7
->csao 9 0.8
->
```

Fig. 7. The PLOT-menu with signals after 20 s experiment.



```
->csao 7 0.7
->bodefreq 0.01 pi
->
```

Fig. 8. The MODEL-menu showing signals and Bode diagram.

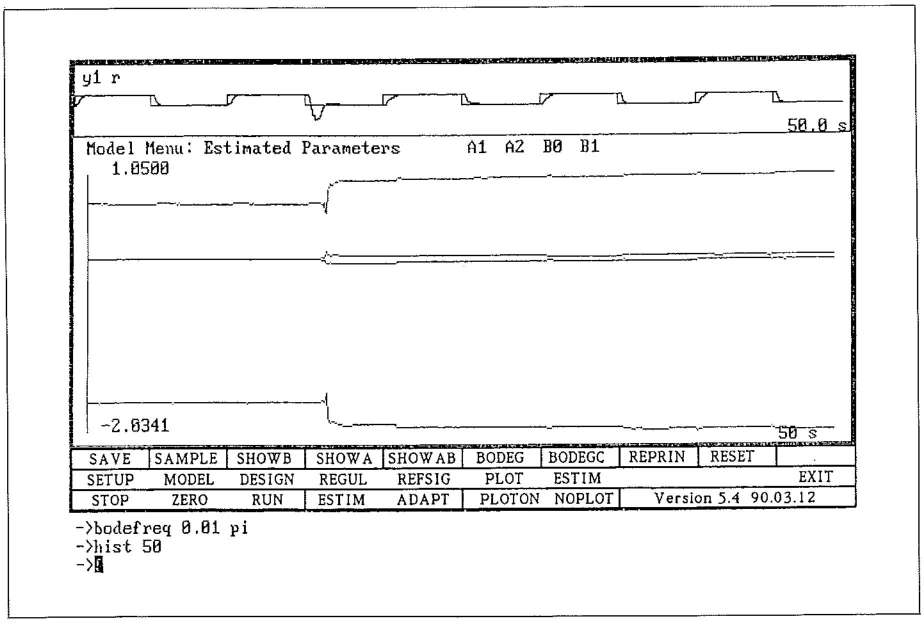
It will now be shown how the system can be used for adaptive control of the DC-servo. In particular we will examine different choices of the design variables for an indirect adaptive controller. Combining the recursive estimator and the pole placement design algorithm gives an indirect adaptive controller [13]. The recursive estimator provides a new process model every sample. Design based on this model gives a new controller every sample. The design parameters are the characteristic polynomials $A_m(q)$ and $A_o(q)$ and the polynomial $A_r(q)$ for introducing integration in the controller. The closed loop system will have the same zeros as the open loop process, i.e., $B^-(q)$ and $B^+(q) = 1$. There are also design parameters in the recursive estimator.

The sampling interval is $t_s = 0.10$ s and the desired closed loop characteristic polynomial is specified as the product of two second-order polynomials (10) with $\omega_m = 5$, $\zeta_m = 0.7$, $\omega_o = 7$ and $\zeta_o = 0.7$. The controller is required to have integral action. The closed-loop system has the same zeros as the open loop system, i.e., $B^-(q) = B(q)$.

The first experiment with the adaptive controller demonstrates tuning of the controller to yield a desired closed loop system. Specifications were entered as in the example above. The upper window in Fig. 8 shows the reference signal and the process output for the system. After 50 s the adaptive controller is stopped. A mouse click in the area marked BODEG draws a Bode diagram of the estimated model. The magnitude and phase responses of (9) are shown in two windows in Fig. 8. The gain curve of the regression filter $|B_f/A_f|$ is also shown. This curve tells us in what frequency range the estimated model is an accurate description of the real system.

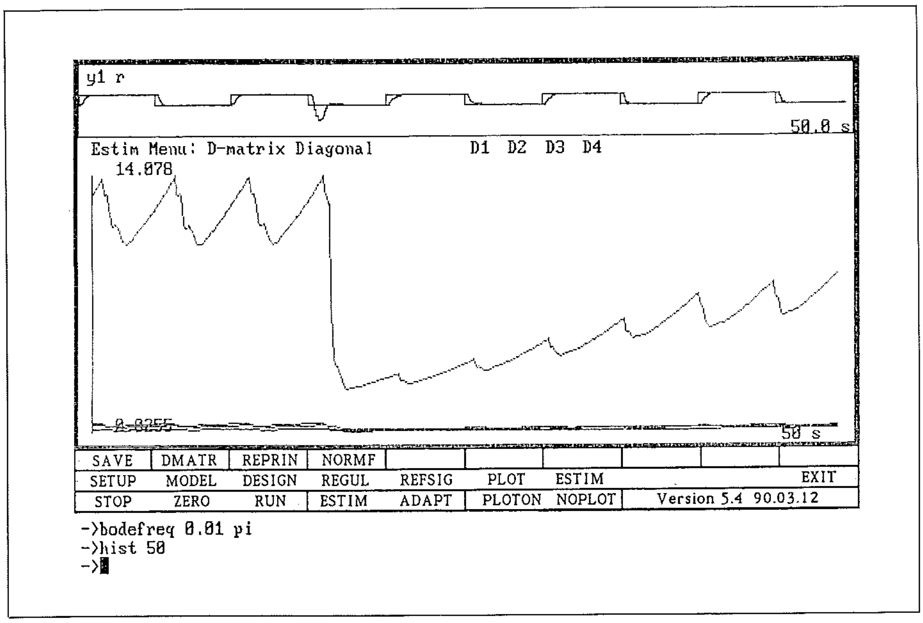
A second experiment with the adaptive controller shows how a change in the real process is detected and handled. The adaptive controller has been running for a while to let the estimated model converge. At $t \approx 12$ s the process dynamics is changed by local feedback on the front panel. The change is drastic and the new open loop system is unstable. The adaptive controller is stopped just before $t = 50$ s. The small window in Fig. 9 shows the reference signal and the process output for the last 50 s. The large window shows the evolution of the estimated parameters. The horizontal time scale and the time for showing estimator history are chosen equal, in order to compare the behavior of signals and variables at certain time instants. We see how the controller adapts to the new process dynamics.

The evolution of the matrix $D(k)$ in the estimator is shown in Fig. 10. Since the controller is stopped and time scales are properly chosen, it is easy to compare the D-matrix and the output signal behavior.



```
->bodefreq 0.01 pi
->hist 50
->
```

Fig. 9. The MODEL-menu showing signals and estimated parameters.



```
->bodefreq 0.01 pi
->hist 50
->
```

Fig. 10. The ESTIM-menu showing the evolution of the D-matrix together with the reference and the output signal.

Education in Automatic Control

The field of automatic control has a strong theoretical foundation that uses many branches of mathematics. Applications are found in all engineering disciplines. Practice of automatic control offers excellent opportunities to use engineering skills. Since feedback control can not naturally be tied to a specific branch of engineering, education in automatic control is organized in many ways. It can be centralized to one group as is done in Lund or it can be spread out among many different departments. We have always been strongly convinced of the advantages of a centralized approach and we are grateful that our university has supported this view. A control laboratory is absolutely essential to reach our dual goal of giving students a strong theoretical foundation and an engineering ability to make systems that work.

Acknowledgment

The authors are grateful to many colleagues who shared their experiences very generously both with respect to course contents and ideas for laboratory experiments. They are also very grateful to many students who have provided challenges and criticism over many years. Particular thanks are due to laboratory staff Leif Andersson, Rolf Braun, Anders Blomdell, and Tomas Schonthal. They are also grateful to the Knut and Alice Wallenberg Foundation, Apple Computer, National Instruments who have provided support and equipment for the laboratories.

References

[1] K. J. Åström, "Education in automatic control at Lund Institute of Technology," in *Proc. 1991 Amer. Control Conf.*, pp. 306-311, Boston, MA, 1991.

[2] K. J. Åström, "A response from academia," in

Preprints IFAC Conf. Advances in Control Education, Boston, MA, 1991, pp. 7-12.

[3] M. K. Masten, "An industrial challenge to control system educators," in *Preprints IFAC Conf. Advances in Control Education*, Boston, MA, 1991, pp. 1-6.

[4] G. Desrochers and G. Saridis. "Educational trends in automation in the United States," in *Preprints 9th IFAC World Congress*, Budapest, Hungary, 1984.

[5] R. Kopacek, I. Genser, A. Troch, and A. Weinmann, "Automatic control education in Austria," in *Preprints 9th IFAC World Congress*, vol. 4, Budapest, Hungary, 1984.

[6] H. Akashi, "Trends in automatic control education in Japan," in *Preprints 9th IFAC World Congr.*, Budapest, Hungary, 1984.

[7] H. Feikema, "Can the efficiency of (control) engineering education be improved? An answer from the field of holistic education and possibilities of a Japanese method," in *Preprints 10th IFAC World Congr.*, vol. 5, Munich, Germany, 1987.

[8] D. M. Auslander and R. Horowitz, "Mechanical engineering control system curriculum," in *Proc. 1988 Amer. Control Conf.*, Atlanta, GA, 1988.

[9] G. F. Franklin and J. D. Powell, "Digital control laboratory courses," *IEEE Control Syst. Mag.*, vol. 9, no. 3, pp. 10-13, 1989.

[10] R. E. Klein, "Using bicycles to teach system dynamics." *IEEE Control Syst. Mag.*, vol. 9, no. 3, pp. 4-9, 1989.

[11] K. J. Åström, *Reglerteori (Control Theory)* (in Swedish). Uppsala, Sweden: Almqvist & Wiksell, 1968.

[12] K. J. Åström and B. Wittenmark, *Computer Controlled Systems--Theory and Design*. Englewood Cliffs, NJ: Prentice-Hall, 2nd ed., 1990.

[13] K. J. Åström and B. Wittenmark, *Adaptive Control*. Reading, MA: Addison-Wesley, 1989.

[14] K. J. Åström, *Introduction to Stochastic Control Theory*. New York: Academic, 1970.

[15] J. G. Balchen, M. Handlykken, and A. Tyssø, "The need for better laboratory experiments in control engineering education," in Akashi, Ed., *Control Science and Technology for the Progress of Society, Proc. Eighth Triennial IFAC World Congress*, Kyoto, Japan, vol. 7. Pergamon, 1981.

[16] M. Mansour and W. Schaufelberger, "Digital computer control experiments in the control group of ETH, Zürich," in *Proc. Eighth Triennial IFAC World Congr.*, Kyoto, Japan, 1981.

[17] J. Biston, J. Dufour, and G. Gilles, "An example of computer control systems practical teaching," in Akashi, Ed., *Control Science and Technology for the Progress of Society, Proc. Eighth Triennial IFAC World Congr.*, Kyoto, Japan, vol. 7. Pergamon, 1981.

[18] M. McDermott, O. Masory, and B. Mooring, "Laboratory for a first course in modeling and automatic control," in *Proc. 1988 Amer. Control Conf.*, Atlanta, GA, 1988.

[19] K. Bonner, M. Marietta, R. Fischl, and P. Kalata, "A generic, hands-on control system laboratory," in *Proc. 1988 Amer. Control Conf.*, Atlanta, GA, 1988.

[20] B. T. Kulakowski, "Automatic control laboratory: New approach to classical problems," in *Proc. 1988 Amer. Control Conf.*, Atlanta, GA, 1988.

[21] Ü. Özgüner, "Three-course control laboratory sequence," *IEEE Control Syst. Mag.*, vol. 9, no. 3, pp. 14-18, 1989.

[22] J. J. Milek. "Microcomputer-based digital control laboratory exercises," in *Preprints 11th IFAC World Congr.*, Tallinn, Estonia, 1990.

[23] K. J. Åström and A.-B. Östberg. "A teaching laboratory for process control," *IEEE Control Syst. Mag.*, vol. 6, pp. 37-42, 1986.

[24] B. Schmidtbauer, "A new first course in analog and digital control," in *Preprints 11th IFAC World Congr.*, Tallinn, Estonia, 1990.

[25] H. Elmqvist, K. J. Åström, T. Schönthal, and B. Wittenmark, *Simnon User's Guide*. Göteborg, Sweden: SSPA, 1990.

[26] O. Dahl, "An interactive environment for real time implementation of control systems," in Barker, Ed., *Computer Aided Design in Control Systems, Preprints IFAC Symp.*, Swansea, U.K. Oxford, U.K.: Pergamon, 1991.

[27] K. J. Åström, "Computer-aided modeling, analysis and design of control systems — A perspective," *IEEE Control Syst. Mag.*, vol. 3, pp. 4-16, May 1983.

[28] D. P. Atherton, "The role of CAD in education and research," in *Proc. Eighth Triennial IFAC World Congress*, Kyoto, Japan, 1981.

[29] M. Jamshidi and C. J. Herget, *Computer-Aided Control Systems Engineering*. Amsterdam, The Netherlands: North-Holland, 1985.

[30] M. Mansour and W. Schaufelberger, "Software and laboratory experiment using computers in control education," *IEEE Control Syst. Mag.*, vol. 9, no. 3, pp. 19-24, 1989.

[31] M. Mansour, W. Schaufelberger, F. E. Cellier, G. E. Maier, and M. Rimwall, "The use of computers in the education of control engineers at ETH, Zürich," *Eur. J. Eng. Educ.*, vol. 9, pp. 135-151, 1984.

[32] W. Schaufelberger, "Teachware for control," in *Preprints 10th IFAC World Congr.*, Munich, Germany, 1987.

[33] W. Schaufelberger, "Teachware for control," in *Proc. 1988 Amer. Control Conf.*, Atlanta, GA, 1988.

[34] W. Schaufelberger, "Educating future control engineering," in *Preprints 11th IFAC World Congr.*, Tallinn, Estonia, 1990.

[35] G. E. Maier and W. Schaufelberger, "Simulation and implementation of discrete-time control systems on IBM-compatible PCs by FPU," in *Preprints 11th IFAC World Congr.*, Tallinn, Estonia, 1990.

[36] MathWorks, *Pro-Matlab User's Guide*. South Natick, MA: MathWorks, Inc., 1990.

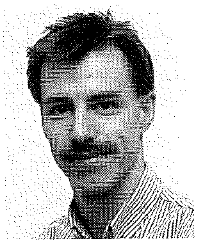
[37] K. Gustafsson, M. Lundh, and M. Lilja, "A set of MATLAB routines for control system analysis and design," in *Preprints IFAC Conf. Advances in Control Education*, Boston, MA, 1991.

[38] M. Lundh, "A package for laboratory experiments in discrete time control," in *Preprints IFAC Conf. Advances in Control Education*, Boston, MA, 1991.

[39] A. Blomdell, "Spread-sheet for dynamic systems — A graphic teaching tool for automatic control," *Wheels for the Mind Europe*, vol. 2, pp. 46-47, 1989.

[40] G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*. New York; Academic, 1977.

Karl J. Åström has been Professor of Automatic Control at Lund Institute of Technology since 1965. Before that he worked for IBM, the Research Institute of National Defense in Stockholm, and the Royal Institute of Technology in Stockholm. His interests cover broad aspects of automatic control, stochastic control, system identification, adaptive control, computer control, and computer-aided control engineering. He has published five books, contributed to several other books, written many papers. He has supervised 31 Ph.D. students and numerous M.Sc. students. He is a Fellow of the IEEE, a member of the Royal Swedish Academy of Sciences (KVA), and vice president of the Swedish Academy of Engineering Sciences (IVA). He has received several awards including the Rufus Oldenburger Medal, the Quazza medal, and the IEEE Control Systems Science and Engineering Award.



Michael Lundh was born in Malmö, Sweden in 1958. He received the M.S. degree in mechanical engineering and the Ph.D. degree in automatic control from Lund Institute of Technology in 1982 and 1992. Between 1982 and 1985 he worked at Saab-Scania AB, Linköping, Sweden, on avionics system development. He worked at Lund Institute of Technology from 1985 to 1992. Presently he is Visiting Researcher at the Center for Industrial Control Science at the University of Newcastle in Australia.