Educational Aspects of CAD Supported Real Time Control

Borut Zupančič, Richard Karba, Drago Matko, and Maja Atanasijević–Kunc

Abstract— **The paper deals with educational aspects of CAD supported real time control. In the Introduction, the historical development of the equipment and appropriate software concerning laboratory exercises in the field of real time control is briefly described. Then the hardware and software equipment used in our education process is briefly described. Emphasis is given to the equipment we developed: a hydraulic-thermal pilot plant, two CACSD program packages with their real time capabilities, and a special program for real time control in addition to emphasizing their connection in a powerful educational system. Some typical exercises from undergraduate courses, e.g., some experiments on the connection of analog and digital computer, identification of the hydraulic process and its level control, as well as some exercises from a graduate course, e.g., the implementation of adaptive digital filtering in real time are described. Some difficulties encountered when applying the theory to practical problems will be discussed.**

I. Introduction

THE department of system theory, automatic control, and cybernetics at the Faculty of Electrical and Computer Engineering in Ljubljana has a very long tradition of laboratory work. The laboratory for analog-hybrid computing and automatic control covers courses on modeling, simulation, automatic control of processes, and computer aided design of control systems.

The study of control engineering has always demanded a theoretical knowledge, but also an appropriate level of skill. For this purpose, the laboratory exercises are very important. When, in the 1970's, an analog computer with parallel logic EAI 580 was included in the educational process, the simulation in real or even faster than real time enabled a methodology by which an understanding of control engineering problems was significantly improved. Later, well-developed simulation languages on large mainframe computers (CSSL III, CSMP III, etc.) became a very good tool in the field of control engineering.

Many years of experience in the fields of modeling and control indicate that computer simulation is a very usable tool from the education as well as research aspects. On the other hand it appears that such exercises can be very tedious. Modern teaching also demands exercises using real pilot plants in a real time environment which show the problems of modeling and control more realistically.

For this purpose, a hydraulic-thermal pilot plant was developed some years ago. Students measured analog signals,

which were displayed on an analog plotter, an oscilloscope, etc. The control was done by our analog computer EAI 580. So students obtained a good insight into continuous modeling and control. Later we connected process computer PDP 11/34, with a process interface, with analog computer EAI 580 and with the hydraulic-thermal pilot plant. So the real process, or one simulated on the analog computer was controlled by a controller which was realized on the process computer. So, the opportunity to create exercises in discrete modeling and discrete real time control was established, too. At the same time, two complex program packages were in development: a program package for analysis and design of control systems ANA, and a program package for simulation of continuous dynamical systems SIMCOS. SIMCOS was expanded with some real time and discrete system simulation capabilities. When the process computer PDP 11/34 was replaced by a personal computer with an appropriate process interface (Burr–Brown PCI 20000) and the old analog computer EAI 580 with the EAI 2000 hybrid system, and some commercially available educational systems were installed, the possibilities of improving courses concerning CAD supported real time control were established. Using such powerful equipment with appropriate CAD software support, which enables exercises in real time environment with hardware in the loop, the interest of students significantly increases. Such an approach greatly helps them later in solving real industrial control problems.

The aim of this paper is to represent the educational process and our experience with laboratory exercises in the field of real time control. So we shall briefly describe our hardware and software, with an emphasis on the equipment we developed ourselves. Some examples of exercises will show the efficiency of this education system for undergraduate as well as graduate education. Some difficulties encountered when applying the theory to practical problems will be mentioned.

II. Hardware Equipment Used in Laboratory Exercises

We shall briefly describe our own developed hydraulic-thermal pilot plant and some commercially available educational systems with which our laboratory has been recently equipped (experimental panel system branch 9 and experimental module system branch UAF9—Elwe, Germany, and Ball and hoop apparatus—TecQuipment, UK). The computer hardware used in laboratory exercises will also be briefly described.
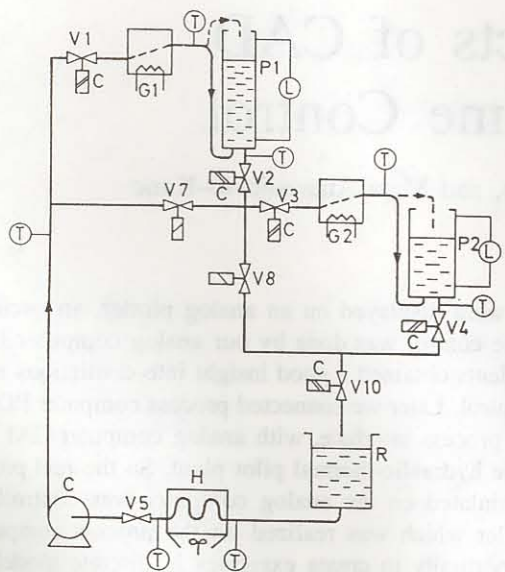
Fig. 1. Scheme of the laboratory pilot plant.

A. Hydraulic-Thermal Pilot Plant

In designing the pilot plant, the following guidelines were considered [5]:

- it should represent a simple laboratory model of a hypothetical process plant, often used in industry;
- from the system theoretical viewpoint it should be a multivariable system consisting of a few subsystems with a moderate number of interrelated systems variables;
- as often as possible, available standard process control components should be included to allow similarity to real process plants, and also to keep investment costs within reasonable limits;
- possibilities for either local or remote control should be provided;
- a convenient degree of flexibility of various configurations was sought, with provisions for easy modifications or extensions; and
- from the educational point of view, it should represent a plant providing basic exercises on the modeling and control courses.

Keeping these guidelines in mind, the plant was designed in the form of a laboratory process system consisting of a hydraulic and a thermal part. Fig. 1 represents the scheme of the pilot plant.

The symbols in the scheme have the following meaning:

C	circulation pump
G1,G2	electric heaters
P1,P2	level tanks
R	reservoir for liquid storage
H	cooler
V1	electromotor control valve
V2,V3,V4,V10	electromagnetic control valves
V5	manually operated valve
V7,V8	electromagnetic on/off valves.

The hydraulic part of the plant consists of two vertical cylindrical glass tanks in which the levels of the liquid can be measured by level transducers. The level tanks are connected with each other and with an auxiliary liquid-storage reservoir in the closed circulation circuit system which also contains a circulation pump, a number of piping cross connections, and remotely controllable electromagnetic valves. The thermal part of the plant is superposed onto the hydraulic part simply by the inclusion of two electrical heaters and a cooler in the piping system. In this way, the working liquid can be heated and also cooled to near normal room temperature. The sensors and actuators mounted in the plant were selected from cheaper standard production programs for process instrumentation. They include:

- two capacity-type liquid level sensors;
- five resistance-type (Pt-100) temperature probes;
- two diffused-silicon differential pressure transducers;
- eight electromagnetic control valves; and
- two standard 2 kW electrical heaters.

The pilot plant is complemented by a separate power and control cabinet containing:

- indication with displays of all measuring variables;
- potentiometers for manual control of valves and heaters;
- electronics for transducers and transmitters;
- electronics for controlling the electromotor and electromagnetic valves, ventilator, pump, and heaters (thyristor regulators);
- galvanic isolation of all measuring signals;
- connectors with analog and digital signals for process computer connection; and
- power supply, power switches, fuses, protection relays.

B. Experimental Panel System Branch 9 and Experimental Module System Branch UAF9

These are two, similar educational systems allowing a presentation of control technology which is very descriptive and easy to understand. Due to the use of field-proven controlled systems, the reference to industrial applications is given in any time. Using the hydraulic process, temperature process, DC shunt-wound machine, and the universal motor about fifteen different exercises can be carried out. Among these are fundamentals of open-loop control, fundamentals of closed-loop control, bang–bang control, P, PI, PID control, feed forward control, cascade control, etc. All processes can be controlled with the included analog control components, with the analog computer EAI 2000, or with the process computer using our packages.

C. Ball and Hoop Apparatus

The above mentioned experimental systems are very descriptive for control purposes, but give very limited possibilities for modeling exercises. For this purpose the Ball and hoop apparatus is very convenient [13].

An essential aim of this system is to illustrate dynamic behavior, and control problems associated with liquid slop, i.e., the dynamic interaction between the material being transported (e.g., liquid) and its moving container (e.g., vehicle). The

vehicle motion is introduced by a rotating hoop and the liquid motion is modeled by a metal ball rolling in the inner periphery of the hoop.

Students do the following experiments:

1) modeling, identification, and analysis of the dynamics of liquid slop,

2) design of velocity and angular position control using a DC servo motor, and

3) the compensation for slop dynamics by negative feedback.

D. Computer Hardware Equipment (EAI 2000, IBM PC, PCI 20000 Burr—Brown)

It is well known that analog-hybrid simulation is very useful for educational work. It is very illustrative because of the speed (true parallelism) and flexibility of an analog computer from which the main idea of simulation, that is solving systems of differential equations by their consecutive integration, draws its origin. When real time simulations of fast processes are needed, analog simulation shows great advantages over other simulation tools.

The new hybrid computer configuration EAI 2000 was installed at our faculty at the beginning of 1988. Because the analog part is controlled with the aid of a microcomputer, it can easily be connected to the digital part obtaining a hybrid system, which enables true hybrid computing, storage of analog models, good documentation features, etc.

The digital part of the hybrid system is the process computer, realized with an IBM PC compatible computer, and the Burr–Brown PCI 20000 system with modules for analog to digital and digital to analog conversions, digital inputs and outputs, timers and counters. This system enables the implementation of our CACSD software equipment with parts that can also operate in real time with hardware in the loop.

III. Software Equipment Used in Laboratory Exercises

A. SIMCOS Simulation Language

SIMCOS is CSSL standard digital simulation language [15], [16]. It is an equation oriented compiler language with FORTRAN as the intermediate language.

Besides all standard simulation language statements, statements for signals and nonlinearities which are shown in Fig. 2 are implemented. Special, discrete blocks, with arbitrary sampling intervals, enable the simulation of hybrid systems. The following discrete blocks can be used: DPID (discrete PID controller), DTRAN (general discrete transfer function), SH (sample and hold element), and DELAY (delay element). The next important improvement to SIMCOS simulation language is the introduction of a so-called general dynamical operator. Realizing this original idea, users have the possibility of choosing the simulation operator to be the integrator or the discrete delay as shown in Fig. 3. In this way, all SIMCOS possibilities can also be used for discrete system simulation.

Real time possibilities are also available in the SIMCOS simulation language. Speed is limited, but sufficient for the educational purposes on real time control courses. Realizing
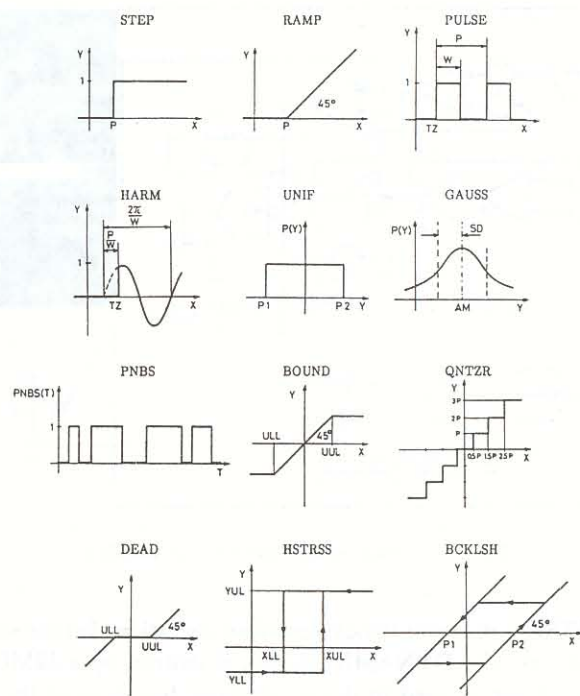

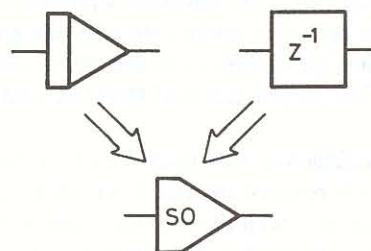Fig. 2.   Signals and nonlinearities included in simulation language SIMCOS.

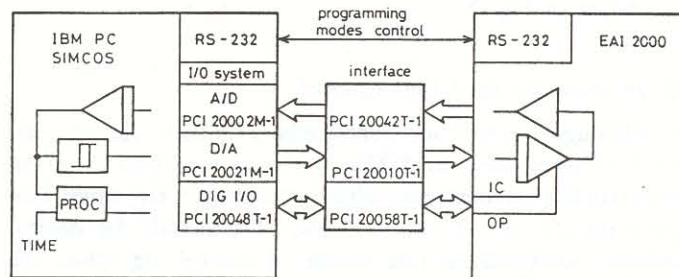Fig. 3.   Realization of general simulation operator.

Fig. 4.   True hybrid configuration.

this feature, we expected to use this simulation tool instead of an expensive analog computer simulation for real time applications, where possible, and as software equipment for the digital part of a real hybrid system (EAI 2000+personal computer). Fig. 4 describes the proposed hybrid system with the EAI 2000 analog computer and the personal computer equipped with PCI 20000 interface.

The SIMCOS simulation language also enables complex experiments with the model-method-experiment concept [2] which is realized by INITIAL, DYNAMIC, and TERMINAL sections. The INITIAL section is represented by a procedural
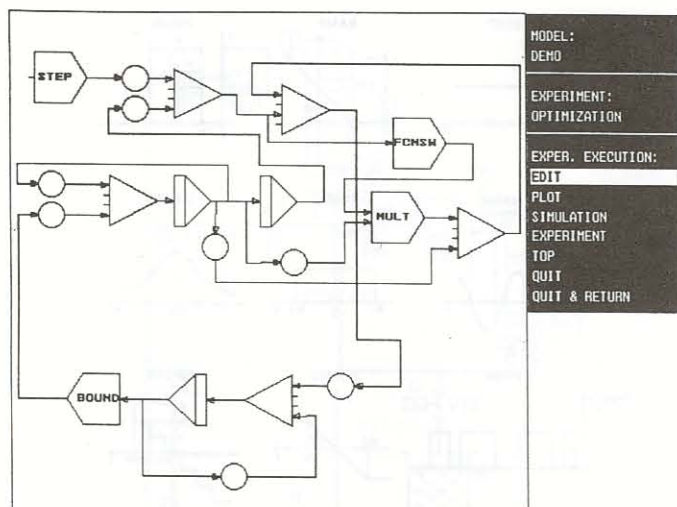
Fig. 5. Outlook of the SIMCOS user interface.

FORTRAN program which describes operations before simulation run. The DYNAMIC section is defined by a SIMCOS program and is used to define all those functions of the experiment which must be executed during simulation in parallel with the model (i.e., input signals, criterion functions,. . .). The TERMINAL section is represented by a procedural FORTRAN program which describes operations after the simulation run. Two experiments, the optimization and the parameter study are available with the preprogrammed INITIAL and TERMINAL sections.

The highly interactive user interface of the SIMCOS simulation language is realized by pull down menus and point and click techniques. It is well fitted to the experimenting concept and also enables the graphic definition of a simulation model, as well as different possibilities for the presentation of results in run time and after simulation. The appearance of the screen is shown in Fig. 5.

B. Program for Real Time Control

Although discrete and continuous controllers can be realized with real time SIMCOS, we have developed a special program that enables more efficient control in real time. This program consists of two modules; 1) a module for control scheme configuration (the choice of control algorithm, the configuration of graphic windows for results presentation, the configuration of technological scheme window, etc.), and 2) of the real time execution module. The latter is realized as a main program which provides, above all, user interactions and results presentations, while the A/D conversions, control signal calculations and D/A conversions are realized in an interrupt routine. Using this program, real time control can be applied to real processes, or processes simulated on the EAI 2000 computer or with the SIMCOS simulation language. The following control algorithms are implemented: PID controller; deadbeat controller; and general dynamic controller. All algorithms have integral windup protection and switching between manual and automatic modes. The controlled variable can be digitally filtered by a low pass filter. All parameters can be relatively

or absolutely changed in real time through the keyboard, and all variables can be graphically or numerically presented in real time or recorded on file for later graphic postprocessing. Besides closed-loop experiments some open-loop experiments are also available.

C. Program Package ANA

ANA is our package for analysis and design of control systems [10]–[12]. The following operations from control system theory are available:

- transformations among different system representations;
- analysis and verification of systems; and
- synthesis of control systems and simulation.

All operations in the package are based on the representations of multivariable systems in the time domain (sampled data series of inputs and outputs, series of self and cross correlation functions), in the frequency domain (transfer function matrix for continuous and discrete systems), in the state space description (for continuous and discrete systems), and in special forms used in simulation.

The package has no real time facilities and is therefore used for off line analysis and design. The typical approach in some exercises consists of the real time data acquisition with LABTECH NOTEBOOK, with off line analysis and design procedure with program package ANA (i.e. powerful identification, optimization,. . .) and with the implementation of the designed algorithms in the real time environment (e.g. with the real time SIMCOS, with the program for real time control, with the EAI 2000 analog computer or with our industrial MMC 90 microcomputer controller) on a simulated or a real process.

IV. EXAMPLES FROM THE EDUCATION PROCESS

Some interesting examples which cover the laboratory exercises on lectures of modeling, simulation, automatic control of processes and computer aided design of control systems will be presented. We shall limit ourselves to those experiments which include our own developed education equipment.

A. Experiments on the Connection of Analog and Process Computer

Such a hybrid system, with the analog part (EAI 2000) and the digital part (personal computer) connected to the PCI 20000 system is very suitable for developing and studying discrete computer algorithms for real time control. Unlike the real time control of the hydraulic pilot plant, where conditions are very nonlinear and time varying, this system enables the study of the ideal situation which is very suitable for undergraduate education. Students must realize a continuous model of a process on the analog computer and a discrete control algorithm using real time SIMCOS or the program for real time control on the personal computer. The following algorithms are included in these exercises.

PID Algorithm: Students must recognize that this is the most applicable algorithm in practice. It is simple for realization, is not time consuming, and is very robust with regard

to process parameter changes and disturbances. The tuning rules which are included in the design option of ANA, and the parameter optimization in ANA and SIMCOS are used for the design of controller parameters.

Deadbeat Algorithm: The advantage of this algorithm is that the design procedure is very simple and educationally convenient. But such a controller is very unrobust and rarely implemented in practice.

Besides these two algorithms, students are also acquainted with an optimal state controller, predictor controller and minimum variance controller. The exercises for graduates also include multivariable and adaptive real time control.

With these exercises, one important thing can also be shown: the calculation of a discrete algorithm causes additional delay in the control loop. Even for a small delay, the response can be quite different compared to the response without delay. Real time simulation on the connection of an analog and digital computer gives a possibility of analyzing this effect. First, the control system is simulated slower than real time, with appropriate time prescalling, so that the calculation delay can be neglected, as it is very small in comparison with sampling time. So accurate or prototype results are obtained. Then the system is simulated in real time and the delay influence can be noticed when comparing both results.

As a concrete example students simulate the process

$$G(s) = \frac{1 - 4s}{(1 + 4s)(1 + 10s)} \tag{1}$$

on the EAI 2000. This process is chosen to show the problems of nonminimal phase systems in a control loop. On the other hand, this process model also shows, how the pure dead time e^{-8s} can be modeled using Pade approximation $(1 - 4s/1 + 4s)$. The discrete PID controller

$$G_R(z) = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{1 - z^{-1}} \tag{2}$$

with sampling time $T_s = 1s$ is realized with the real time simulation option in SIMCOS. The optimal parameters are calculated by the optimization option. The same optimization method is built in ANA and SIMCOS. This is the so-called "EXTREM" method, a kind of searching method that does not need evaluations of gradients. Besides the criterion function, the user can also define arbitrary constraints and different conditions for optimization termination. For our example the criterion function

$$S_e^2 = \sum_{k=1}^{100} e^2(k), \tag{3}$$

where $e(k)$ is the difference between the unity step reference change and the appropriate controlled variable is chosen. Optimization gives the following controller parameters: $q_0 = 5.96$, $q_1 = -10.34$, $q_2 = 4.49$. A part of this exercise is also to analyze the influence of disturbances in the control system. When the Gaussian noise with standard deviation $\sigma = 0.08$ and bandwidth BW $= 4$ Hz disturbs the controlled variable, the control system does not behave satisfactorily to the reference
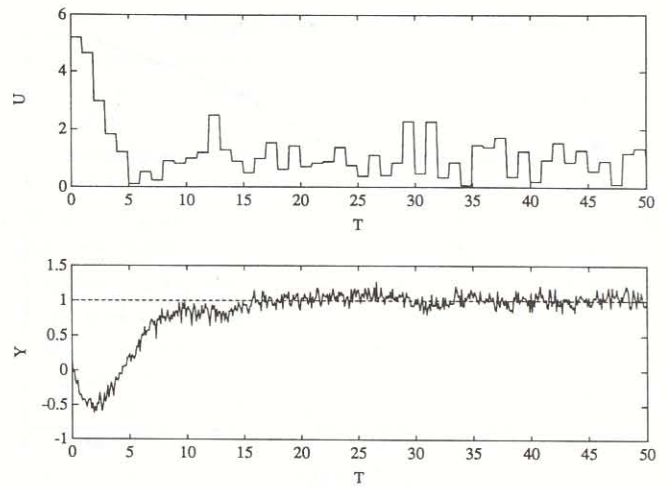

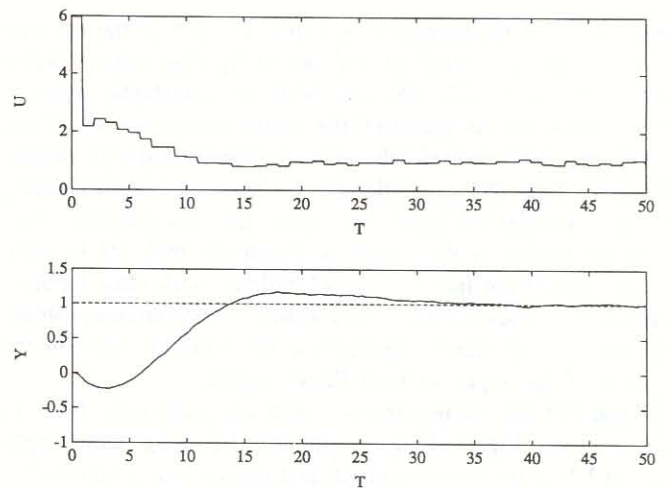Fig. 6.   Control and controlled variable without filtering.

Fig. 7.   Control and controlled variable with filtering.

unit step change, as can be seen in Fig. 6. So the students also implement filter

$$G_F(s) = \frac{1}{2s + 1} \tag{4}$$

for disturbance elimination. As PID algorithm this filter is also realized in SIMCOS in discrete form

$$G_F(z) = \frac{0.0244 + 0.0244 z^{-1}}{1 - 0.9512 z^{-1}} \tag{5}$$

which is the discrete equivalent obtained from continuous prototype filter using bilinear transformation and sampling time $T_s = 100$ ms. So the filter operates with a sampling time ten times faster as controller what is usually the case in control systems. Fig. 7 shows the control and the controlled variables to the unit step reference change. The results are satisfactory.

B. Identification and Level Control of the Hydraulic—Thermal Pilot Plant

The scheme of the laboratory pilot plant is shown in Fig. 1. A hydraulic subsystem with pump C, valve V1, level tank P1, valves V2, V8, and V10, and the storage reservoir R is
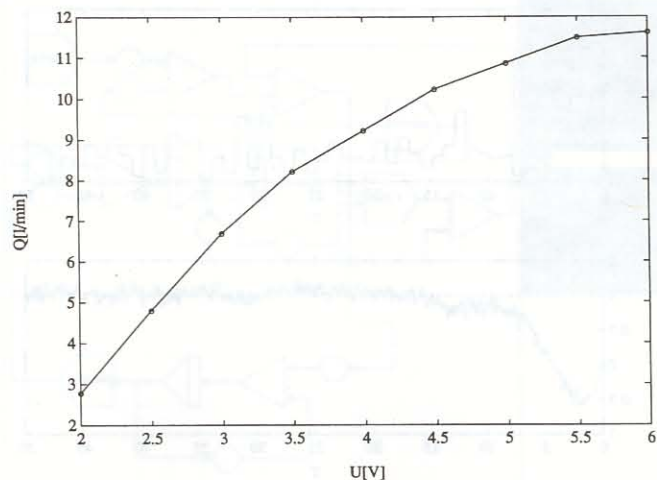
Fig. 8.   Flow/voltage characteristic of electromagnetic valve.

Fig. 9.   Input pulse signal, the output signal of the real process and the output signal of the identified model.

considered for the purpose of control. The aim of the exercise is to control the level in tank P1 with electromotor valve V1. The valves V2, V8, and V10 are constantly opened. It is important to measure the static characteristic of the electromagnetic control valve, which is controlled with voltage 0–10 V. This characteristic can be measured automatically using a special program developed for this purpose. This program measures the times in which the tank P1 is filled up at appropriate input valve V1 voltage with closed output valves. Fig. 8 shows this characteristic. When students obtain this curve they choose appropriate the working point in the middle of the approximately linear region.

Then I/O data of the process, with sampling time $T_s = 1s$ are recorded. Fig. 9 shows the input pulse signal with amplitude 0.3 V at the working point, and the measured liquid level in the tank P1. When the I/O measurements are obtained the exercise is followed by identification with ANA. It is realized by a black box method [6], [9], where the structure is identified and parameters are estimated. The structural identification is based on the choice of linearly independent vectors from the information matrix (the matrix, which is obtained from I/O data). The parameters are estimated by the least square method. The model is obtained in the block companion, discrete state space description. After transformation the discrete transfer function model

$$G_p(z) = \frac{0.026z^{-1}}{1 - 0.99z^{-1}} z^{-3} \qquad (7)$$

is obtained. Fig. 9 also shows the response of this model to the pulse input.

With this model, different control algorithms with program package ANA can be designed and implemented on the hydraulic real plant using real the time facilities of SIMCOS or the special program for real time control.

This exercise reveals many difficulties when students apply the theory to practical problems. It turns out that students usually have few problems using the methodology for control system design, as these methods are dealt with in detail in lectures, supported with CACSD tools and previously well
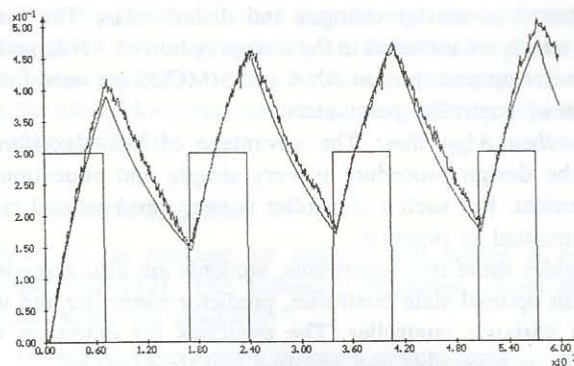
tested with the aid of simulation. The problems often appear in the following, quite practical aspects of realization:

• the understanding of static designing in the sense of used actuators and sensors;
• the choice of appropriate working points for control and controlled signals;
• the manual control to obtain working point conditions;
• the problems of switching from manual to automatic mode and vice versa;
• the problems of bounded physical signals which often demand the redesign of control algorithms to avoid these problems (e.g., the integral wind up);
• alarms during real time control;
• interactions during real time control;
• more sophisticated disturbances (not applying only to the process inputs and outputs, as is usually considered in simulation studies); and
• the problems of nonlinear and time varying behavior of the real processes. As the linear model is valid only at the working point, to obtain approximate linear responses the inputs should be small.

These are very important practical problems to which the emphasis is given in this exercise. They are usually not considered in the simulation environment.

C. Implementation of General Predictive Controller on a Hyrdraulic Pilot Plant

Graduate students in the department of automatic control also have lectures on adaptive control. One of the laboratory exercises for these students is to implement the general predictive controller [3], [4] on the hydraulic plant. Adaptive control is realized with the recursive, least square identification method and with a general predictive controller (GPC).

D. Real Time Adaptive Filtering

Digital filtering is extremely important in real time control. The adaptive eliminator [7], [14] is an efficient method for eliminating corrupting noise, if a reference noise correlated to the corrupting noise is available. The adaptive eliminator shown in Fig. 10 is especially simple for sinusoidal noise.

There are two inputs: the primary input into which the corrupted signal is fed, and the reference input which is fed
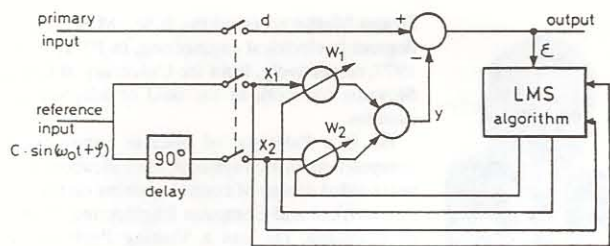
Fig. 10. Adaptive eliminator for sinusoidal interferences.

Fig. 11. Corrupted and filtered EMG signal.

by the reference noise correlated with the corrupting noise. The components x_1 and x_2 are two sinusoidal for $\pi/2$ shifted signals of the frequency that is to be eliminated. The weights w_1 and w_2 are adjusted with the adaptive LMS algorithm

$$w_1(t) = w_1(0) + \int_0^t 2\mu \in x_1(\tau)\,d\tau,$$

$$w_2(t) = w_2(0) + \int_0^t 2\mu \in x_2(\tau)\,d\tau. \qquad (8)$$

The constant μ influences the settling time and the bandwidth of the adaptive eliminator.

In this exercise, the filter is used to eliminate the corrupting 50 Hz power line interference from the very small EMG (electromyographic) signal in real time. The reference input is fed by a 50 Hz voltage signal taken from a wall outlet. The filter is realized on the analog computer EAI 2000. The appropriate results are shown in Fig. 11.

V. CONCLUSION

The described laboratory equipment, with appropriate software enables a very efficient educational process for courses in real time control. Analog computers are ideal for real time simulations because they enable the simulation of extremely fast processes in ideal situations. The connection of analog and personal computer in hybrid is most suitable for studying discrete control algorithms for real time control. For such exercises, SIMCOS is also important because it represents, with its real time capabilities, a very cheap alternative to expensive analog computer simulation when processes are slower. On the other hand, SIMCOS represents an appropriate software for the digital part of the true hybrid system.

The hydraulic pilot plant represents a real process where students find problems similar to those they meet later in practice. Using it for laboratory exercises the students interest increases significantly.

Such an educational system is appropriate not only for undergraduates but also for graduates because interesting exercises from real time adaptive control and filtering can be realized, too.

The trends in control education, where expensive and rather nonflexible pilot plants are replaced by simulated ones with an appropriate graphical interface [1] are also being considered. SIMCOS, with its real time capabilities, would represent a simulation background of such a system, and its graphic model design tool would enable the direct building of technological schemes. So students would observe on screen what happens in a plant in a real time; they would use several graphical screens with simulated measurement instruments, they would also influence a control system in a user friendly way. Having in mind that each student can experiment with his own "plant," the advantage of such an educational system is evident.

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Borut Zupančič received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the University of Ljubljana, Slovenia in 1977, 1979, and 1989, respectively.

He is an Assistant Professor on the Faculty of Electrical and Computer Engineering, University of Ljubljana, Slovenia, and is responsible for lectures on control systems, simulation of dynamical system, and computer aided design of control systems graduate study. He was a Visiting Professor at the Institute for Control Engineering, Darmstadt, Germany, from 1988–1989. His major research emphasis is on the fields of simulation of dynamical systems and computer aided design of control systems.

Drago Matko received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering, in 1971, 1973, and 1977, respectively, from the University of Ljubljana, Slovenia for work in the field of adaptive control systems.

He is a Professor of discrete control systems, computer controlled systems, identification and computer aided design of control systems on the Faculty of Electrical and Computer Engineering, University of Ljubljana. He was a Visiting Professor at the Institute for Control Engineering. Darmstadt, Germany, as a Humboldt Fellow from 1980–1982, and in 1984, 1985, and 1987. His research interests are in adaptive systems and computer aided design of control systems.

Rihard Karba received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering, from the University of Ljubljana, Slovenia.

In 1977, he joined the Faculty of Electrical and Computer Engineering, University of Ljubljana, and in 1987 became Professor of automatic control, where he is currently responsible for lectures on: elements in automatic control, modeling of processes and multivariable systems (on undergraduate and graduate levels). His major research emphasis is in the fields of dynamical systems modeling and simulation, multivariable control design, and modeling and simulation in pharmacokinetics.

Maja Atanasijević–Kunc received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Ljubljana, Slovenia, in 1981 and 1984, respectively

She is a Teaching Assistant on the Faculty of Electrical and Computer Engineering, University of Ljubljana, Slovenia. Her research interests involve control of multivariable systems and simulation of dynamical systems.