Process Control 1971-1972 : Final Report Project

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PROCESS CONTROL 1971-1972

FINAL REPORT
PROJECT 71 50/U33
SWEDISH BOARD FOR TECHNICAL DEVELOPMENT

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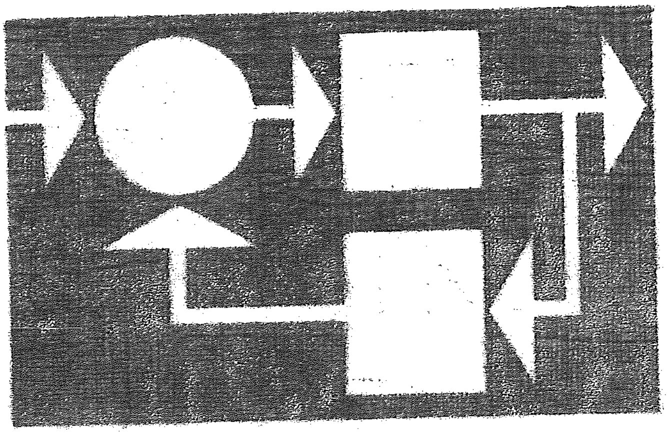

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PROCESS CONTROL 1971 - 1972

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ABSTRACT

This report surveys the results of the process control project at the Division of Automatic Control of Lund Institute of Technology. The project covers system identification, adaptive control, computational control, real time computing, system theory and applications. Among the results of the project are 9 papers, 29 technical reports. Two PhD theses and 18 MS theses have also been completed within the framework of the project.

5. REAL TIME COMPUTING

Real Time Computing Laboratory
Real Time Control Algorithms
Real Time Programming
Interactive Synthesis Programs

LOGGER
SYNPAC
SIMNON

6. APPLICATIONS

Thermal Power Plants
Nuclear Power Station
Power Systems
Paper Machine Control
Thermal Process
Identification
Determination of Thermal Diffusivity
Control
Economic Systems
Biological Control
Miscellaneous

7. SYSTEM THEORY

Linear System Theory
Multivariable Systems

8. TECHNOLOGY ASSESSMENT

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1. INTRODUCTION.

The project is part of a long range program in the area of process control [1]. Earlier results are reported in [2], [3], [4] and [5]. A detailed program for the activity during 1970/71 is presented in [6].

Most research at the Division of Automatic Control has been centered around the process control project. The work has been organized so that three scientists directly supported by the Swedish Board for Technical Development (STU) have acted as project leaders in System Identification (I. Gustavsson), Computational Control (K. Mårtensson) and Real Time Computing (J. Wieslander). One research engineer, C. Källström, has been providing programming support. Apart from the four members directly supported by STU important contributions have also been given by students and staff of the institute.

The research plan presented in [6] has been followed. Due to hard volontary work by B. Wittenmark the research on adaptive systems has been carried out according to plans in spite of a significant reduction in the grant originally applied for. Significant results have thus been obtained in the area of self tuning regulators. The access to the real time computer installation has significantly contributed to the progress of the project. Within the framework of the real time computing project programs for interactive design of control systems have been developed. These programs have proven surprisingly effective design tools. During the year the process control laboratory has also been provided with flexible interfaces and additional processes. The real time computing laboratory was used for 3200 hours during the year.

The interaction between the research and the graduate program has increased. Most term papers for the courses in "Process Control in the Paper Industry" and "Software for Online Control" were of direct interest for the research project.

In collaboration with users and manufacturers of process control equipment and STU a seminar on process control was also arranged. The practical details were handled by the secretary for industrial liaison. In collaboration with Mr. K. Anvret of Svenska Teknologföreningen we also arranged a new course on "Processdatorer och processreglering".

2. SYSTEM IDENTIFICATION.

The research on system identification has mainly continued along the lines in the research program [1], i.e.

- comparison of different identification methods, particularly when applied to data from real processes,
- development of algorithms and program packages making identification applicable in practice to model building of industrial processes,
- studies of theoretical problems in connection with identification and parameter estimation,
- application of identification and parameter estimation techniques to model building of different processes, including design of suitable experiments and model analysis.

Off-line methods as well as real time identification methods are studied. The project has now reached a state which enables us to identify single input single output linear systems with relatively small effort. The experiences gained from identification of many different processes make it possible to design suitable experimental conditions, to handle data efficiently, to choose appropriate identification methods and to analyse the obtained models. Also problems with identification of multivariable and nonlinear systems have been considered but still many problems remain before the identification of such complex systems can be performed in a similarly efficient way as single input single output systems.

Comparison of Different Identification Methods.

A lot of experiences has been gained from the identification of many real processes by different methods. So far some of the experiences have been reported, e.g. in

Gustavsson, I.: Comparison of Different Methods for Identification of Industrial Processes, Automatica, Vol. 8, pp. 127 - 142, (1972),

and in

Åström, K.J., and Gustavsson, I.: Identification and Modelling of Industrial Processes, Colloque Franco-Suedois Conduit de Procédés, IRIA, Paris, October, 1971.

Åström, K.J.: Modelling and Identification of Power System Components in E. Handschin ed. "Real-Time Control of Electric Power Systems", Elsevier, Amsterdam - London - New York, 1972.

Comparisons of different identification methods are also found in the reports

Eklund, K.: Linear Drum Boiler-Turbine Models, Report 7117, Nov., 1971,

Åström, K.J., and Källström, C.: Identification and Modelling of Ship Dynamics, Report 7202, March, 1972,

Lindahl, S., and Ljung, L.: Identification of Power Generator Dynamics from Normal Operating Data, Report 7210, May, 1972.

In most cases only single input, single output systems have been considered. For such systems the maximum likelihood method has given the best results for black box models. On the other hand it has been found that it may be of great importance for accuracy etc. to exploit available à priori physical knowledge of the process. It has been pointed out that comparisons between model parameters or between transient or frequency responses for different models may not be relevant if the ultimate aim of the identification is to synthesize a control strategy from the model.

The estimation of impulse response functions with the Fast Fourier Transform method and via prewhitening and computation of the cross correlation function has been compared. In general both methods give fair estimates, but they fail if the impulse response slowly fades out. The Fast Fourier Transform method fails if the signal to noise ratio is less than approximately one. For a low noise level the Fast Fourier Transform method gives a considerably better accuracy, even for white noise input. In general neither method converges asymptotically to the true values. A preliminary report

> Ljung, L.: Pilot Estimation of Impulse Response Functions

has been written. The methods have been applied to the power generator data.

Programs.

Subroutines to be used for different identification methods are available on the computer Univac 1108 at Lunds Datacentral in Lund in the program library built up by our division. For some methods, e.g. the maximum likelihood identification of discrete, linear, multiple input, single output systems and the parameter estimation in linear state space models, more elaborated program packages for identification and model analysis have been developed. Those program packages make it easier for the user to perform identification.

Some of the programs have also been written for the process computer PDP 15. Experiences from identification on a rather small computer show that

i) it is possible and even feasible to make identification on a rather small computer,

ii) it is very handy and saves a lot of work to use interactive programs for data handling, identification and model analysis.

An interactive program for the multiple input, single output case is implemented on the PDP 15. A description is found in the MS thesis

Almquist, R.: Program för Maximum Likelihood Identifiering på PDP 15, (Programs for Maximum Likelihood Identification on PDP-15), RE-103, February, 1972.

An extended version of this program is now in use. The program is command oriented and a display unit is used for some of the output from the program like diagrams etc. This program has made it possible to let rather untrained people perform model building of different processes via identification. The implementation of this interactive program is a continuation of the work on an 'Automatic Identifier'. This work will be followed up next year. Spectral analysis programs have also been implemented on the process computer and used for time series analysis.

Theoretical Problems.

When trying to identify real processes a lot of problems of principle nature also arise. Such problems have been studied along with model building of different processes via identification techniques. Some of the studied problems are discussed below.

Identifiability.

An important question particularly for parameter estimation in state space models is the identifiability problem. It seems to be very difficult to give simple criteria for the general case, so that the identifiability can be easily checked. For special cases, however, some criteria have been developed.

The problem of identifiability is closely related to observability of nonlinear systems and to convergence properties of recursive identification methods. It has also been noticed that identifiability problems may frequently occur if vector difference equations are used as models for multivariable systems. Related problems with vector difference equations have e.g. been studied by Mr. K. Smuk, Prague, Czechoslovakia, who visited our division for one month during 1971 under the exchange program between the Czechoslovak and Swedish Academies of Sciences.

Input Signals.

Another important question is the choice of suitable input signals for identification experiments, in order to receive maximal information about process and disturbances without violating possible limitations on signals etc. In practice we have succeeded rather well to design reasonable input signals using à priori knowledge of the process like step responses. However, the signals used may not be optimal.

Programs designed for optimal control of nonlinear systems have been used to determine optimal input signals for very simple systems. A serious drawback of this method is the assumption that the system has to be known in order to enable the design of an optimal input sequence. In a work partly performed at the Division of Automatic Control Mr. L. Keviczky, Budapest, Hungary, has studied how to do suboptimal input signal synthesis recursively and simultaneously with identification of the system. He also studied a corresponding off line aspect of this problem, i.e. given an experiment, it is then possible to determine a better input sequence for another identification experiment with the process in order to improve the model for the process. Mr. L. Keviczky has been a guest at the division from May to July, 1972.

Many identification methods require persistently exciting input signals in order to give reasonable estimates. The concept of persistently exciting in the frequency domain has been treated in

> Ljung, L.: Characterization of the Concept of 'Persistently Exciting' in the Frequency Domain, Report 7119, Nov., 1971.

nator and the numerator. Investigation of the problem how to test for common factors in two polynomials when the uncertainty of the parameters is considered has started.

The properties of the likelihood function for the dynamic system estimation problem are currently under investigation. For large signal to noise ratios the loss function asymptotically has a unique minimum, if the model

$$A^*(q^{-1})y(t) = B^*(q^{-1})u(t) + \lambda C^*(q^{-1})e(t)$$

is used. For other structures of the model several stationary points may exist even for low noise levels. For a first order system, however, only one stationary point exists for the model

$$y(t) = \frac{B^*(q^{-1})}{A^*(q^{-1})} u(t) + \lambda \frac{C^*(q^{-1})}{D^*(q^{-1})} e(t)$$

Drift and Errors in Measurements.

The influence of drift and errors in measurements on the parameter estimates has been studied by Mrs. C. Banyasz, Budapest, Hungary. She worked at the division from May to July, 1972, as a guest scientist and dealt with identification problems. It was shown that isolated errors in the measurements do not influence very much on the estimates of the parameters of the transfer function if the maximum likelihood method was used. If ordinary least squares method was used the influence was disastering. The noise model was heavily influenced. Drift in the measurements gave rise to a very slow mode in the estimated model and therefore drift should be compensated for before the identification.

Applications.

The available programs for identification and parameter estimation have been used for modelling of a great number of different processes. Examples are given in the following which also shows the extensive cooperation with industry and with other institutions.

Paper Machine.

We are collaborating together with STFI (Svenska Träforskningsinstitutet), Stockholm, on a paper machine control project. A first part of the project is to develop models for different parts of a paper machine. Our institute has participated in the planning of suitable identification experiments and the evaluation of the results. Until now four experiments on an experimental paper machine have been performed and the data have been analysed with the maximum likelihood method. Preliminary results are given in

Häggman, B.: Arbetsrapport från identifieringsförsök 1&2 på XPM, utförda 13.12.1971. (Identification of XPM part 1&2(provisional)).

Häggman, B.: Arbetsrapport från identifieringsförsök 3&4 på XPM, utförda 16.3.1972. (Identification of XPM part 3&4 (provisional)).

Experiments on an industrial full scale paper machine are planned in order to verify the obtained results.

Nuclear Reactor.

Data from identification experiments at the Halden Boiling Water Reactor have been analysed with Maximum Likelihood technique. Results from single input disturbance experiments are published in

> Olsson, G.: Maximum Likelihood Identification of Some Loops of the Halden Boiling Water Reactor, Report 7207 (B), March, 1972,

and also in a joint paper

> Roggenbauer, H., Seifritz, W., and Olsson, G.: Identification and Adjoint Problems of Process Computer Control, Paper, session 2, Halden Meeting on Computer Control of Nuclear Reactors, Loen, Norway, May 29 - June 2, 1972,

presented at the Enlarged Halden Group Meeting in Loen, Norway. Later multi-variable identification experiments have been performed and some runs have been analysed in an MS thesis,

> Carlsson, S.: Maximum Likelihood identifiering av reaktordynamik från flervariabla experiment, (ML Identification of Reactor Dynamics from Multivariable Experiments) RE-111, June, 1972.

Nowhere the model order exceeds four. A low order multivariable stochastic model of the reactor plant is under preparation.

Boilers.

The experiments performed at the thermal power station, Öresundsverket, in Malmö have been analysed in different ways. Identification with the maximum likelihood method and parameter estimation of state space models have been performed. Results are published in a PhD thesis,

Eklund, K.†: Linear Drum Boiler - Turbine Models, Report 7117, Nov., 1971.

Some of the results are also given in

Eklund, K.†: A Comparison of a Drum Boiler-Turbine Model to Measurements and Models Obtained by Identification, Preprints of the IFAC 5th World Congress, Paris, 1972.

The measurements will also be used for parameter estimation in nonlinear models.

The division has also been involved in the planning of experiments on a ship boiler together with Institutionen för Skeppsmaskinteknik, CTH, Göteborg, and Kockums Mekaniska Verkstad, Malmö. Probably the data from the forthcoming experiments will be analysed using our identification program packages.

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† Dr. K. Eklund is now with the Axel Johnson Institute for Industrial Research, Nynäshamn, Sweden.

Mixer Settler.

At the Division of Chemical Engineering experiments with a mixer settler have been performed in collaboration with our division. The data have been analysed by several identification methods. Some preliminary results were published in

Aly, G. and Wittenmark, B.: Dynamic Behavior of Mixer Settlers Part II, (Accepted for publication in the Journal of Applied Chemistry).

Power System Components.

A presentation of identification in connection with power system components was given in

Åström, K.J.: Modelling and Identification of Power System Components, Report 7116B, Oct., 1971,

together with a discussion of certain identification problems. The material was also presented at the Brown-Boveri symposium on Real-Time Control of Electric Power Systems.

The dynamics of a power generator have been studied in detail. Results from identification of normal operating data from a power generator are given in

Lindahl, S., and Ljung, L.: Identification of Power Generator Dynamics from Normal Operating Data, Report 7210, May, 1972.

The data were obtained from Dr. Stanton at Purdue University. The results show the difficulty to use normal operating records for model building but on the other hand also some knowledge about suitable model order was gained. The results also show the suitability of identification of impulse responses for the determination of casuality relations, time delays etc.

Thermal Diffusion Process.

Identification of a system governed by a partial differential equation has been performed. The experimental process is a one dimensional heat diffusion process. The inputs of the process are the end point temperatures of the rod. The outputs of the process are the temperatures in seven equally spaced points on the rod. The process has been modelled by ordinary difference and differential equations.

Discrete model: Linear, time invariant, discrete models subjected to disturbances that are stationary random processes have been identified. It has turned out that adjacent modes s_k of the theoretical model

$$G(x,s) = \sum_{k=1}^{\infty} \frac{K_k(x)}{1+s/s_k}$$

which have gain factors $K_k(x)$ of the same sign are represented by a single mode in the discrete models. The sum of the gain factors $K_k(x)$ of adjacent modes is the gain factor of the single mode in the model. The theoretical model relates the temperature at a point x on the rod to the left end temperature. It has been found that discrete models of rather low order, e.g. 5th order, are sufficient to describe the dynamics of the process extremely well for all sampling rates.

Leden, B.: Identification of Dynamics of a One Dimensional Heat Diffusion Process, Report 7121, Nov., 1971.

State space models: Different identification techniques have been used for the determination of the thermal diffusivity of the rod. It has turned out that the thermal diffusivity can be extremely well determined from PRBS experiments using parameter estimation of state space models. Errors in measuring the thermal diffusivity are 0.01%. The errors in methods earlier described in literature are 1%. The study has been done in collaboration with Dr. M.H. Hamza, University of Calgary, Canada.

Ship and Airplane Dynamics.

Measurements of the rudder and heading angles for a ship were performed by two students. The data were used for identification of a third order model and the results are presented in

Åström, K.J., and Källström, C.: Identification and Modelling of Ship Dynamics, Report 7202, March, 1972.

It was shown that hydrodynamic derivatives could be determined if also the across ship velocity component is measured. New measurements have been performed in collaboration with Kockums Mekaniska Verkstad, Malmö, but the data are not analysed yet. Corresponding measurements with airplanes have been received from SAAB, Linköping.

Interior Climate.

Identification has been used as a tool for modelling different processes that are studied in the research project on control of indoor environment. Models obtained by identification have been compared to the models built on physical knowledge. For some processes it was indicated that it was very difficult to get good models based on construction data.

Biological Processes.

Contacts with researchers at the Lund University Hospital have been established as well as with researchers at Karolinska Institutet, Stockholm. Some joint work has been done. Results from one part of this collaboration are reported in

Hagander, P.: ML Identification of the Workload-Heart Rate Dynamics in Man Using PRBS, Report 7208B, April, 1972.

Macroeconomic Systems.

The problem of determining a macroeconomic model from highly aggregated data is in several respects similar to the problem of modelling the dynamics of an industrial process. The main differences are that the macroeconomic data sets are usually short and that the input signals are usually generated using feedback. To get some feeling for the problem and the possible applicability of methods developed for identification of industrial processes an

3. ADAPTIVE CONTROL.

The research on adaptive control has been conducted along the lines given in the research program [1], i.e.

- 0 Analysis of special adaptive systems.
- 0 Exploitation of real time identification algorithms.
- 0 Use of optimal stochastic control theory.

Special Adaptive Systems.

The analysis of special adaptive structures have been continued. The regulator proposed by Marsik is investigated in

Andersson, P.O., and Olofsson, T.: Undersökning av Marsiks adaptiva regulator, (Investigation of Marsik's Adaptive Controller), RE-102, December, 1971.

It is shown that the regulator works well in many cases but that it may be sensitive to input signals. Examples where a steady state gain is never achieved with periodic inputs are constructed.

Real-Time Identification.

A fairly straight forward way of constructing adaptive regulators is to assume separation of identification and control. The problem then reduces to a design problem for a system with known parameters and a real-time identification problem. Least squares identifiers have been tried earlier. Some exploratory studies to use a parameter tracker based on an extended Kalman filter have been initiated in

Pernebo, L.: Adaptiv reglering av linjära system med hjälp av utvidgat Kalman-filter, (Adaptive Control using Extended Kalman Filter). RE-110, August, 1972.

In this work it is demonstrated that the technique can be applied successfully to a first order system. Difficulties have been encountered with a second order system. The nature of the difficulties are not yet clearly understood. Since the problem is both nonlinear and stochastic it is expected that a significant amount of exploratory simulation is needed before the problem is clearly understood.

Self-Tuning Regulators.

The problem of controlling a system with constant but unknown parameters can be considered as a special case of the adaptive control problem. If the problems are approached through stochastic optimal control theory both problems lead to similar analysis and formidable computational problems. In the case of systems with constant but unknown parameters it is, however, meaningful to ask for algorithms which, although they are not optimal, will converge to the optimal strategies that could be computed if the parameters were known. The earlier initiated investigation of such algorithms have been continued. Some results were presented in

Åström, K.J., and Wittenmark, B.: On the Control of Constant But Unknown Systems, Paper 37.5, Fifth World Congress of IFAC, Paris, June, 1972.

To find control algorithms for systems with unknown but

MS project has been started. The data used is from the UK economy and has kindly been provided by Dr. J. Bray of the Programme of Research into Econometric Methods of the Dept. of Economics at Queen Mary College, England.

Necessary and sufficient conditions for a signal to be persistently exciting are given. The effect of filtering a persistently exciting signal is also discussed. Relations between the notion of persistent excitation and the possibility to predict the signal are established.

Convergence Properties

Asymptotical convergence properties for the generalized least squares method have been investigated. It has been shown that

i) for large signal to noise ratios the parameters converge to the true values (the global minimum of the loss function),

ii) for small signal to noise ratios the method most often can converge to several different parameter combinations, which one depending on the initial guess of the parameter values (several local minima of the loss function).

The results have been verified by simulations. The generalized least squares method has also been used to identify several real processes, e.g. a nuclear reactor, a thermal diffusion process and a distillation column. In all cases those practical identification examples gave several minima and sometimes it was not obvious which one was the correct one.

The maximum likelihood method applied to time series analysis has also been studied. It has been proved that the likelihood function asymptotically has a unique minimum. If the model order is too high the transfer function will be correct, but common factors will appear in the denomiconstant parameters leads to the possibility of finding self-tuning regulators. Such regulators can be very useful in practice due to their potentials of eliminating tedious tuning procedures. The approach is persued in

> Åström, K.J., and Wittenmark, B.: On Self Tuning Regulators, Report 7209B, May, 1972.

This paper has been accepted for publication in Automatica. The research has been conducted along different lines.

- Implementation and testing of the algorithms on different processes.
- Experimental investigations into improved algorithms through simulation.
- Theoretical analysis.

The basic algorithm has been applied to several of the experimental processes in the process control laboratory. A new simple process has also been designed to make it possible to study the effects of time delays. The improved algorithms aim at increasing the classes of systems to which the algorithm can be applied and to improve the convergence rate. The algorithm can be trivially extended to include tuning of feed forward compensators. The problem of nonminimum phase systems is now understood and an algorithm which handles this case has been written. An even simpler version of the original algorithm has also been provided.

Under the exchange program between the Czechoslovak and Swedish academies of sciences we also had Dr. Peterka as a visiting scientist for three months. During this period the multivariable case was investigated. An algorithm was developed for systems having a vector difference representation.

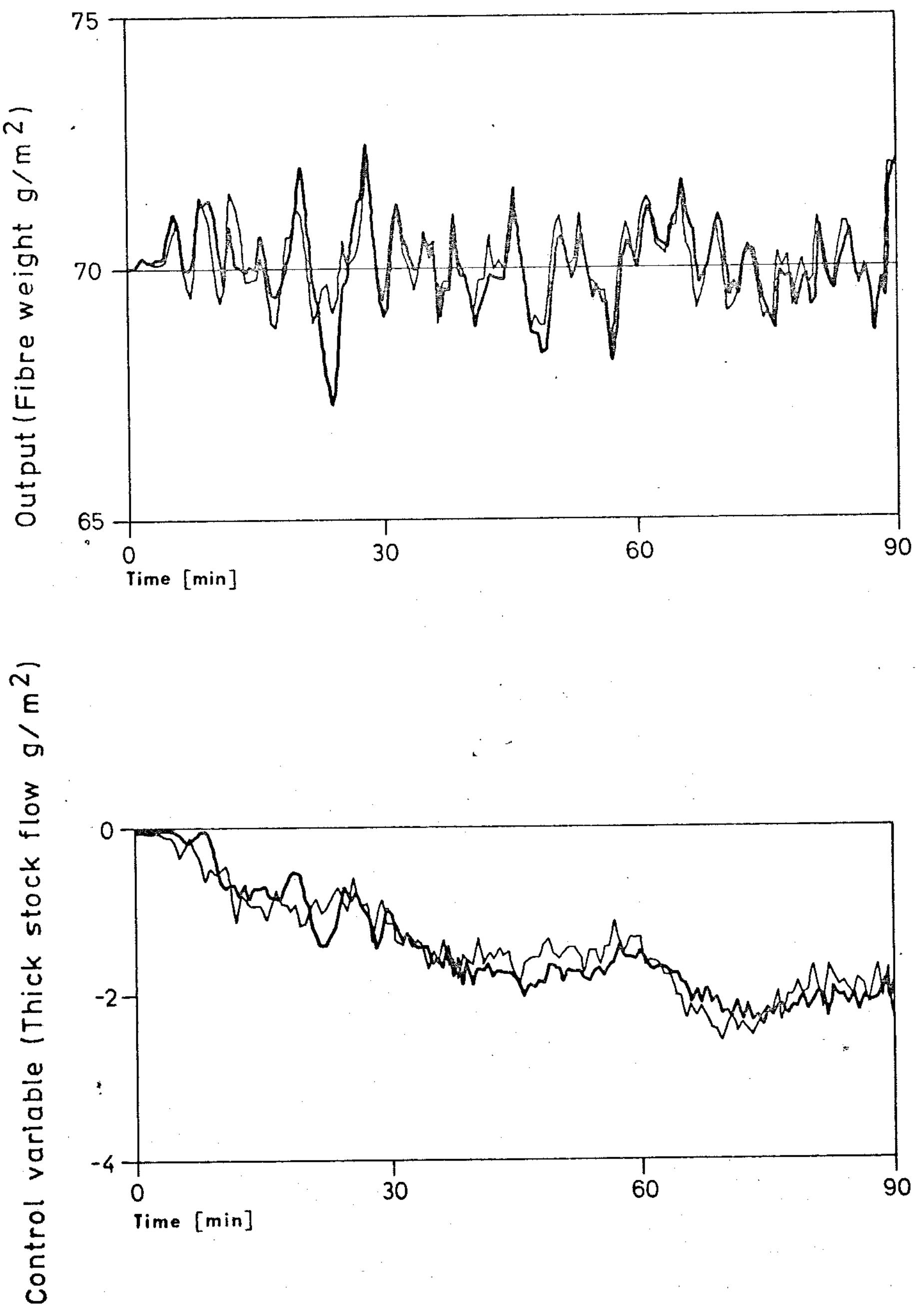

Fig. 3.1

Results of simulation of a self tuning regulator for basis weight control of a paper machine. The full lines show the results using a self tuning regulator and the thin line the results with a minimum variance regulator based on off-line identification of the process. The disturbances used in the simulation are actual measured plant data. The curves show that after about 30 minutes of operation the self tuning regulator will give practically the same performance as a minimum variance regulator designed from a known process model.

To simplify the experimental work on the algorithms two conversational programs have been written which make it possible to simulate and evaluate the self-tuning regulators in a flexible manner.

The theoretical analysis of the algorithms are being extended. The fundamental theorems which characterize the closed loop systems obtained if the parameter estimates converge have been extended and simplified. The corresponding results for non-minimum phase and multivariable systems will require a significant effort. Some basic problems on identifiability of closed loop systems which are closely related to the convergence of the self-tuning regulators have also been posed.

Learning Systems.

The problem of convergence of self-adjusting regulators can also be put in the framework of learning systems. Some techniques which can be used to establish convergence with probability one are discussed in

> Ljung, L.: Convergence Concepts for Adaptive Structures, Report 7218B, August, 1972.

The theory is applied to a simple self-tuning algorithm and to an automatic classifier. Some classification algorithms are also studied in

> Bosrup, L., and Gustavi, J.O.: Självlärande klassificering, (Self-learning Classification), RE-97, Sept. 1971.

> Eriksson, S., and Lindkvist, H.: Parametriska metoder för självlärande klassificering, (Statistic Classification without Teacher), RE-107, April, 1972.

4. COMPUTATIONAL CONTROL

The work has been persued along the two main lines given in the research program. Development of basic algorithms and numerical methods for optimal control. During this year we have also made a few exploratory studies to investigate the possibilities of using interactive design programs for synthesis of control system. The interactive programs are discussed in Section 5.

The program library

The development of the program libraries have continued. Even if many programs are written by the teaching staff it is extremely valuable to have a professional programmer to enforce uniformity and good programming practices.

A special study of algorithms to transform continous time linear systems to discrete time linear systems have been made. The results are given in

> Källström, C. : Computing exp A and $\int$ exp (As)ds, to appear.

The algorithms for transforming lossfunctions, and stochastic systems have also been studied. A paper on numerical computation of Lyapunov functions

> Hagander, P.: Numerical solution of $A^TS + SA + Q = 0$, Information Sciences 4, (1972), 35-50.

has also been published.

During this year the programs for maximum likelihood identification of single output multiple input systems have been put into the computing library. A preliminary version of a maximum likelihood identification program for multivariable systems with arbitrary structure has been written. This program achieves flexibility through the use of a function minimization technique which uses function evaluation only. The user only has to supply code which defines the model structure. The program has been compared with a program which exploits gradients and second derivatives. On a particular problem, concerning estimation of parameters in a mathematical model methods which were based on evaluation of functions (V) functions and gradients (V and V_θ) and functions, gradients and second derivatives (V, V_θ and $V_{\theta\theta}$) were compared. The results obtained are summarized below

Table 4.1

Summary of function evaluations and computing times for different methods for parameter estimation

	First order model Function evaluations	 Time	Second order model Function evaluations	 Time
Powell (V)	149	150	443	440
Fletcher-Powell with numerical gradient (V)	179	180	730	730
Fletcher-Powell (V,V_θ)	42	160	55	270
Newton-Raphson ($V,V_\theta,V_{\theta\theta}$)	6	100	9	160

A program package for the simulation of large linear systems has also been written. To make it easier to transfer programs and data between the two computers UNIVAC 1108 and PDP-15/35, programs for this purpose have been developed and added to the program library.

Optimal Control of Non-linear Systems

The existence of efficient and powerful computational methods has more and more proved to be necessary for the applicability of optimal control theory to complex industrial processes. Consequently the research efforts have been concentrated on these problems, and computer programs as well as new theoretical approaches to algorithms have been subject to research. In addition, some feasibility studies on different industrial processes have been carried out, and these have provided valuable information about the advantages and disadvantages of different computational methods.

A new method, the constraining hyperplane technique, has been developed for the class of state-variable constrained problems. The numerical solution of these problems has for long constituted a difficult problem within optimal control theory, and has often hampered the application of the theoretical results. Computational experiments indicate that this new method is very efficient compared with existing methods, and it seems as if the technique constitutes a breakthrough for a large class of problems. The idea behind the method is to approximate the feasible region in state-space with a suitable region, e.g. a halfspace generated by a hyperplane, in the mixed state-control-space. Thus the problem is converted into a problem which is easily handled by existing methods for control variable constrained problems. The technique is described in

Mårtensson, K. "A Constraining Hyperplane Technique for State Variable Constrained Optimal Control Problems", Report 7206, March 1972.

In the report comparisons are made with different previously suggested methods. It is wortwhile to point out that the method has proved applicable to problems of a complexity not considered previously.

The existence of a computational method for state variable constrained problems has made it possible to carry out a feasibility study of optimal control of a travelling overhead crane. This work was done in collaboration with the Swedish company ASEA, through Mr Å. Rullgård. The problem originates from the container terminal outlined in Fig. 4.1, and the problem is to determine the control strategies of the crane so that minimum time goods handling is achieved.

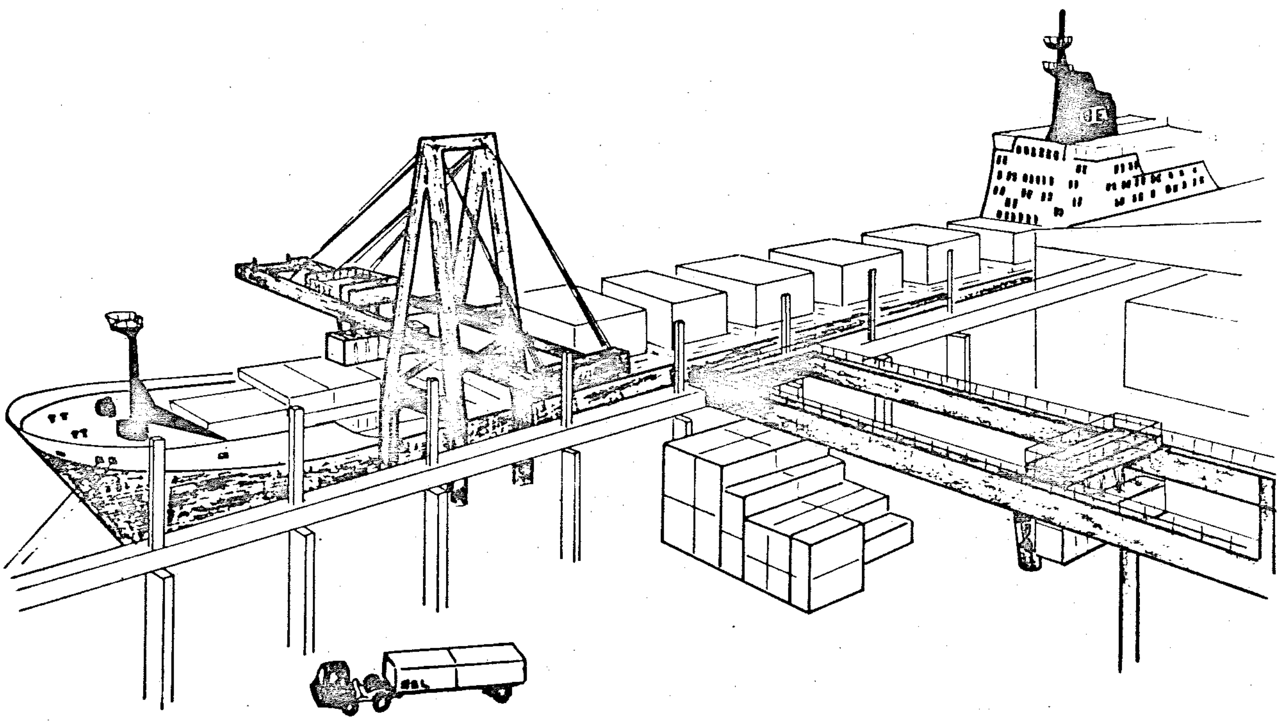

Fig. 4.1

Various subproblems for different mathematical models of the crane have been studied, and the results are reported in

Mårtensson, K. "Optimal Control of a Travelling Overhead Crane - a feasibility study", Report 7206, March 1972.

In Fig. 4.2 the approximate time-optimal trolley acceleration u_1 is shown together with the corresponding trolley velocity x_2. Both the acceleration and the velocity are constrained, and from Fig. 4.2 it can be seen that the velocity exhibits a rather unexpected appearance and reaches the boundary twice. One of the advantages of the constraining hyperplane techniques as

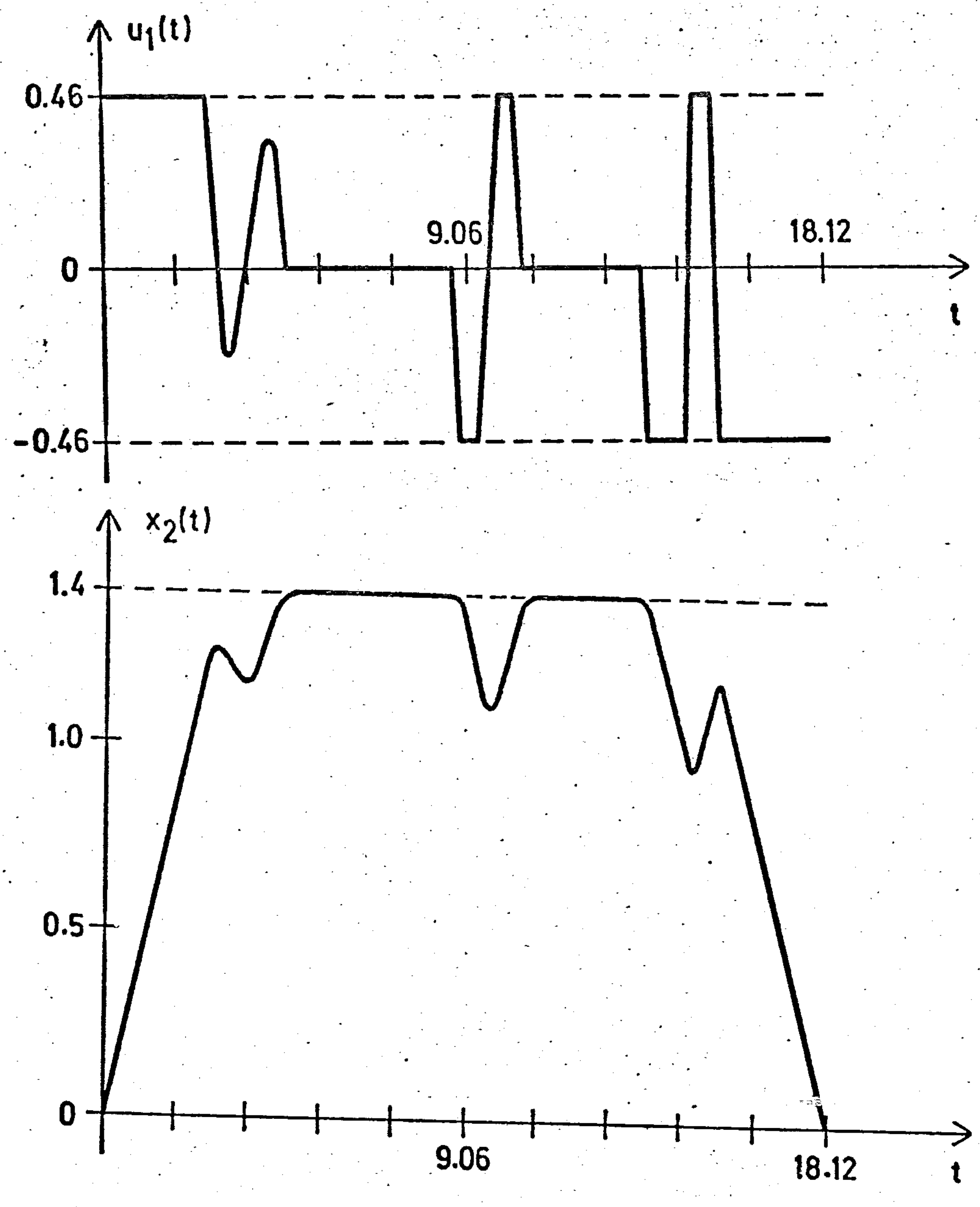

Fig. 4.2

compared with some of the existing methods is that this property of the optimal solution is not necessary to know à priori. Apart from the presentation of the optimal strategies, different computational aspects are discussed in the report, e.g. necessary modifications of the computer program and the possibility to implement the optimal strategies.

Optimal control of an acid sulfite cooking process has been studied in collaboration with the Department of Chemical Reaction Engineering, Chalmers University of Technology. This study well illustrates the applicability of optimal control theory to rather complex industrial processes. The results from a preliminary study are reported in

Nilsson, L.O. "Optimal styrning av sulfitkokare" (Optimal Control of the Acid Sulfite Cooking Process), Thesis Report RE-108, March 1972.

The results from a more detailed study where different technological constraints are considered will be presented in a fortcoming report.

Methods for Constrained Function Optimization

A thorough knowledge of different possibilities to solve ordinary function optimization problems is extremely valuable for the possibility to solve optimal control problems. There are many reasons to this. One is that the computation of optimal control strategies very often requires a function optimization subprogram, e.g. to carry out the minimization of the Hamiltonian. Another reason is the analogy between finite-dimensional problems and optimal control theory.

A new approach to the constrained function optimization problem is presented in

Mårtensson, K. "A new Approach to Constrained Function Optimization", Report 7112, September 1971. (Accepted for publication in the Journal of Optimization Theory and Applications).

In this report some new algorithms are also derived, and future work will consider the possibility to generalize these results and thereby derive new computational methods for optimal control problems.

5. REAL TIME COMPUTING

This project is performed in the real time computing laboratory with the PDP-15 computer and various laboratory processes. The purpose of the project is to learn about real time computing processes. The laboratory is also a useful tool for teaching since it enables the students to develop a feeling for the interactions between the real world and mathematical models. Two projects have been persued. Experiments with real time control and interactive synthesis.

Real Time Computing Laboratory

The laboratory which was put into operation last year has been used extensively. The PDP-15 computer was used for 3200 hours during the year. In the light of the experiences obtained the laboratory has also been somewhat modified.

a. A floating point processor has been installed.

b. A hard copy unit has been connected to the display unit. At the same time the interface to the display was rebuilt to decrease disturbances.

c. The analog-digital cabling interface was redesigned and extended. The connectors were changed to a mechanically stronger type.

d. A remote data aquisition terminal (A H-P Coupler-Controller with digital voltmeter) was acquired. In order to interface this to the PDP, a EIA-compatible teletype interface was built into the PDP.

Several simple processes that could conveniently be used to study process control algorithms experimentally were investigated. The possibility to use processes at other institutes were investigated. Contacts were taken with departments of chemical engineering, power engineering and architecture (ventilation and thermal control). After the studies it was decided to implement two new laboratory processes; a pH-control system and a prototype process control system which admit level, concentration and temperature control.

To facilitate the experimental work an interface for the small analog computers has also been developed. The interface is connected to the internal bus of the analogue computer and provides an interface for analogue signals through tiepoints and mode control signals. The interface delivers an oscilloscope trig pulse as the analogue computer is switched to the operate mode. The remote connector panel connects the analogue- and logical signals of the PDP-15 to the interface.

Real Time Control Algorithms

The systematic analysis of real time control algorithms has been continued. Particular emphasis has been given to minimal variance regulators. See

> Borisson, U. and Holst, J.: Real Time Computing II. Minimal Variance Control on Process Computer, Report 7108(B), September 1971.

The implementation of linear quadratic regulators and Kalman filters have also been investigated. Trade-offs between storage and computing time for different algorithms have been studied. A flexible algorithm which allows rejection of measurements which deviate too much from their predicted values and corresponding restructuring of the Kalman filter has been written and simulated on the thermal diffusion process. See

Källström, C. and Åström, K.J.: Real Time Computing III, Implementing Linear Filtering and Control Algorithms, Report 7122, December, 1971.

These algorithms have been studied in connection with the graduate courses on process control and real time computing. A significant effort has been used to study algorithms for self tuning regulators. This work is still continuing.

Real Time Programming

The graduate course in real time programming given in the spring 1971 by J. Schoeffler was concluded during the fall. The examination contained as a part actual implementation of some algorithms on the PDP in the RSX-environment. A task several of the students choose was to implement the self tuning regulator on the mechanical ball rolling device (bommen). J. Schoeffler returned in January 1972 to give some additional seminars.

Experience in real time programming has during the year been gained through the implementation of the RSX-monitor on the PDP and through the writing of the LOGGER program system (See below).

A three days course entitled "Processdatorer och Processreglering" (Process computers and process control), was given to an audience of people from industry in cooperation with "STF-ingenjörsutbildning" in October 1971.

Interactive Synthesis Programs

A major obstacle towards a wide spread use of many of the powerful results of modern control theory in practice is the lack of suitable programming tools. The availability of interactive program packages may be a possibility to remove this obstacle. A major effort has thus been devoted to the development of such packages.

Some words on the general design philosophy may be appropriate. Interaction between a program and the user can take two quite different forms. The program calls the user to input numeric data or to choose between some alternatives concerning the next operation, or the user gives commands to the program. These commands can contain arguments to further specify the users interactions. The principal difference between the two methods is that in the later case the user has the initiative, it is thus easy e.g. to go back and correct mistakes which may be quite a problem if in the former case the program keeps asking the "wrong" questions. Programs of both types have been developed and their respective ease of use have been judged. The result has been that further work in this area will be directed towards command driven programs despite the fact that they are somewhat more difficult to write. The program must read a command line, decode it and act accordingly. To solve this program, an initial effort has been made to write some command decoding subroutines that are or will be used by all interactive programs. Using the same command decoding routines means also that the command structure will be the same for all programs, which is an advantage to the user from a learning point of view.

Several projects have been completed during the year. The idea has been to try different approaches on problems of moderate size to get experience. The following packages have been completed.

```
>SAMP
>SRIC
>TYPE L

L
  0.11407        0.70872E-01
 -0.48707        0.36073
>USRIC
>YSRIC
>SHOW U 1 2
>,Y 1 2 3 4
>EXPAN A←A COL 3 2 B
>ZEROM TEM 2 4
>ALTER TEM 1 3
#-2
>,,2 4
#-2
>EXPAN A←A ROW 3 2 TEM
>ZEROM B 4 2
>ZEROM TEM 2 2
>ALTER B 3 1
#2
>,,4 2
#2
>EXPAN L←L COL 3 2 TEM
>TYPE L

L
  0.11407        0.70872E-01   0.00000        0.00000
 -0.48707        0.36073       0.00000        0.00000
>ZEROM TEM 2 1
>EXPAN X0←X0 ROW 3 2 TEM
>SAMP
A    C     THE MATRICES HAVE NOT THE SAME NUMBER OF COLUMNS
>ZEROM TEM 4 2
>EXPAN C←C COL 3 2 TEM
>SAMP
>USRIC
>YSRIC
>SHOW U 1 2
>SHOW Y 1 2 3 4
```

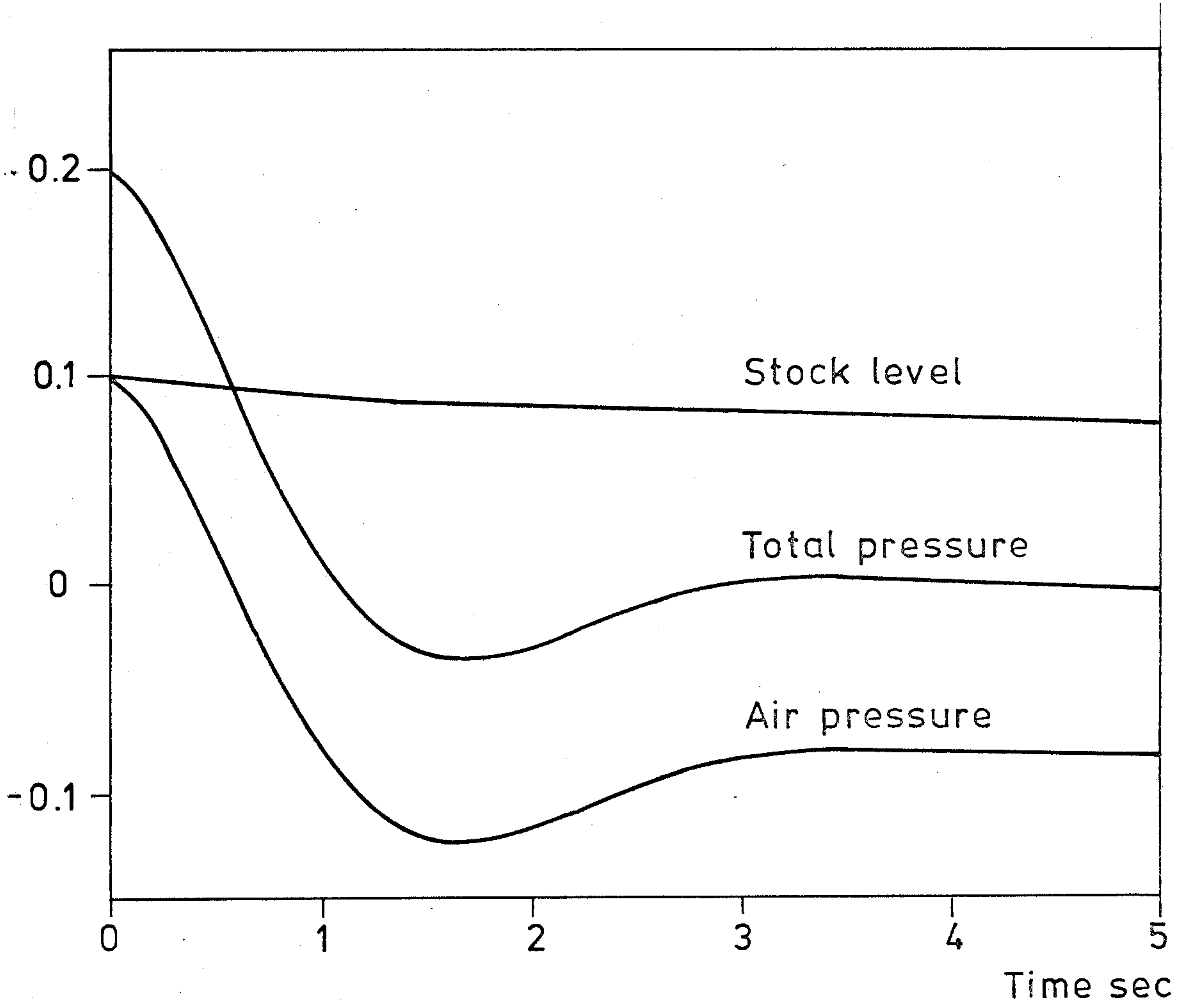

Fig. 5.1
Shows the dialog between the users and the computer when a headbox regulator is designed using SYNPAC.

LOGGER

This is a program which runs in the RSX system and is an aid in starting and running data aquisition and control experiments. It consists of a series of tasks that set up the experiment environment (number of variables, sampling interval, experiment length etc), perform the actual analog I/O, records data on mass storage, converts data from mass storage to standardized form on magnetic tape among other things. The program system takes advantage of the multi-programming environment and the writing have given valuable insight into the problem of writing real time programs.

SYNPAC

This is an interactive design tool for the control engineer. It uses linear quadratic control theory to design linear feed-back regulators. It features among other things conversion from continous time to discrete time models simulation of open or closed loop system, computation of the regulator feedback matrix plotting of the resulting input and output time functions, general matrix handling and a first version of a MACRO command facility. A description of SYNPAC is available in

Novén, T.: SYNPAC - Ett interaktivt program för syntes av reglersystem, (An Interactive Program for Synthesis of Control Systems), Report RE-104, February, 1972

Wieslander, J.: Computer Aided Design of Linear Feedback Regulators using Linear Quadratic Control Theory, Presented at the ONLINE 1972 Conference, Brunnel Univ., Uxbridge, England, September, 1972.

SIMNON

This is a simulation package for non-linear systems. The non-linear differential equations are input in symbolic form using an ALGOL-like syntax, compiled into a pseudo-code that is then interpreted during the actual simulation phase. By this approach the turn-around time between the inputting of the equations and the simulation has been decreased considerably compared to the conventional method with coding the equation in a separate FORTRAN subroutine. See

Elmqvist, H.: SIMNON - Ett interaktivt simuleringsprogram för olinjära system, (An Interactive program for simulating Non-linear Systems), Report RE-113, July 1972.

The program SYNPAC has been tested in a course on system techniques for mechanical engineers. It has been shown that it is possible to teach the fundamentals of linear quadratic theory and to get the students desgin fairly complex control systems using the program package in a fairly short time (a few days). It is therefore our current belief that the development of packages of this type can prove to be a very effective way of transferring knowledge from research into applications. It is therefore planned to make an extension of SYNPAC and to try it on an industrial audience.

We have also established contacts with other groups who are working on related problems and arranged for an exchange of programs and experiences.

6. APPLICATIONS

After the completion of the boiler study we have not had an application study of the same magnitude. The applications have instead been carried out within the framework of the other programs as well as in connection with the graduate program.

Thermal Power Plants

The final report on the thermal power plant

> Eklund, K.: Linear Drum Boiler - Turbine Models, Report 7117, November, 1971.

appeared during the period. Some results obtained in this work were presented at the fifth Congress of IFAC

> Eklund, K.: Comparison of a Drum Boiler - Turbine Model to Measurements and Models obtained by Identification, Paper 5.3 Fifth Congress of IFAC, Paris, June, 1972.

The work on simple non-linear boiler models reported earlier was also published as

> Åström, K.J. and Eklund, K.: A Simplified Non-Linear Model of a Drum Boiler - Turbine Unit, Int. J. Control 16, (1972) 145-169.

This work has made it possible to obtain a good insight into the dynamic properties of a drum boiler. In particular it has been found that many essential features of a boiler can be characterized by a simple non-linear function which expresses output power as a function of drum-pressure and steam valve setting. See Fig. 6.1.

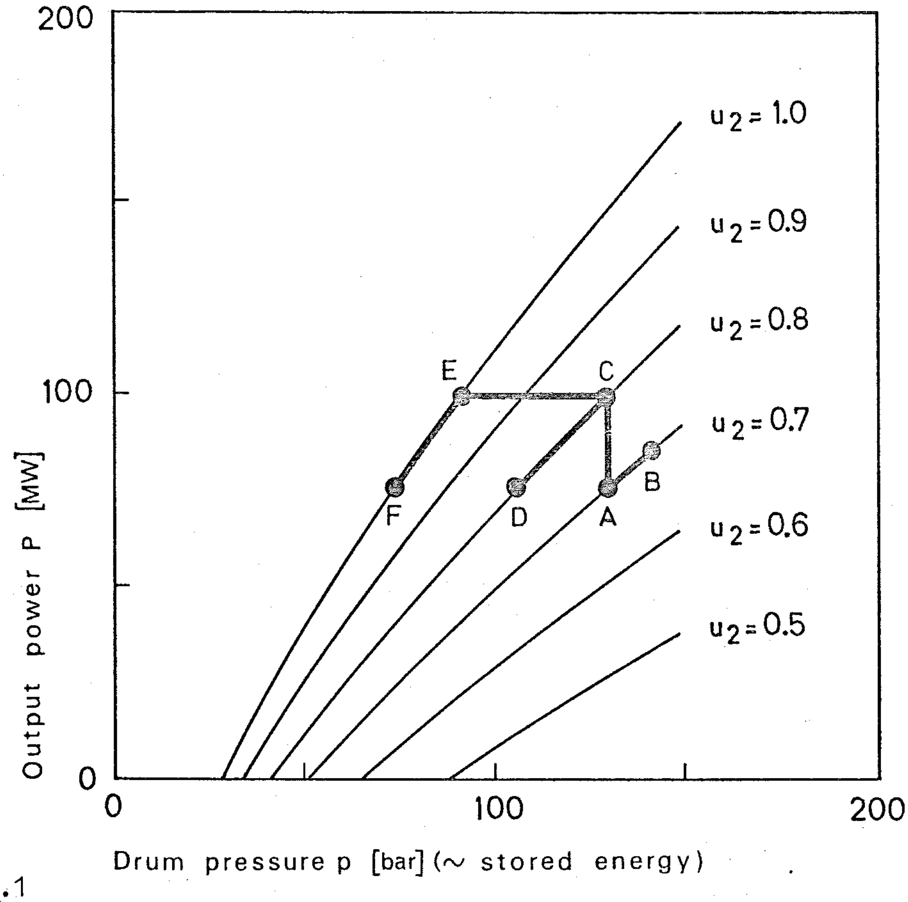

Fig 6.1

Graph showing the output power P for a drum boiler as a function of drum pressure p and steam valve setting u. The non-linear model is simply

$$\frac{dp}{dt} = \alpha(P(u_2,p) - P_{in}) \qquad (*)$$

where P_{in} is the input power. The qualitative properties of the drum boiler are easily determined from the graph. Assume that the plant is operating in steady state with a given drum pressure and a given steam valve position u_2=0.7 (point A of the diagram). If the input power is increased the drum pressure will slowly decrease according to (*) until a new steady state condition with output power matching input power is achieved (point B of the diagram). If the control valve is suddenly opened the output power is suddenly increased (from A to C in the diagram). If the control value is then kept constant the drumpressure and the output power will then slowly decrease according to (*) until a new steady state is reached at D, where output power matches input power. If at C the steam valve is manipulated it is possible to maintain constant output power until the valve is fully open at point E. The output power will then drop according to (*) to the new steady state at F. From the diagram it is thus easy to find the storage capacity and the amount of power that can be released on short notice.

Nuclear Power Station

The collaboration with the OECD Halden Reactor Project at Halden has been continued. We have thus participated in the planning and evaluation of dynamics experiments. Some results are reported in

Carlsson, S.: Maximum Likelihood identifiering av reaktor dynamik från flervariabla experiment (Maximum Likelihood Identification of Reactor Dynamics using Multivariable Experiments), Report RE-111, July 1972.

Gustaf Olsson was also invited to act as a commentator on the session Power - Nuclear Plants at the IFAC World Congress. See

Olsson, G.: Power - Nuclear Plants, Commentator's report. Fifth IFAC Congress, Paris, June, 1972.

Some of the results of the identifications of the Halden Reactor have been reported at a symposium in May 1972. See

Roggenbauer, H., Seifritz, W. and Olsson, G.: Identification and Adjoint Problems of Process Computer Control. Paper, Enlarged Halden Group Meeting on Computer Control, Loen, Norway, May, 1972.

A more detailed report describing modeling of the Halden Reactor dynamics is found in

Olsson,G.: Maximum Likelihood Identification of Some Loops of the Halden Boiling Water Reactor, Report 7207, March, 1972.

Power Systems

The work on power systems has been continued in two directions: Modeling of power system components and design of feedback laws for power systems.

The modeling and identification of power generator dynamics based on experiments performed by Dr K.N. Stanton has been completed and is documented. Variations in angular velocity, terminal voltage, reactive and active part of armature current were recorded during normal operation. Preliminary analysis of the data showed that the most decisive input-output pair is electric torque and angular velocity. It has been shown that it is not possible to explain the variations in angular frequency without modeling the external world. In

> Lindahl, S. and Ljung, L.: Identification of Power Generator Dynamics from Normal Operating Data, Report 7210, May, 1972.

the external world is assumed to be another generator giving a fifth order model with ten unknown parameters. Such a model can reasonably well explain variations in angular velocity and terminal voltage.

The results are encouraging but show that it is desirable to introduce an artificial input signal.

The analysis of basic physical laws governing a power system has been documented. The report

> Lindahl, S.: A State Space Model of a Multimachine Power System, Report 7118, November 1971

describes a method to determine the equations for a power system on standard state space form. The resulting linear model is valid for small perturbations from an operating point and in a timescale from 0.5 sec. A computer program is written to form the system matrices from construction data. The number of generators that can be handled is limited only by the core memory of the computer. With the current installation at LDC it is possible to model power systems with 10 generators, 30 modes and 50 lines.

The model is used to design a linear feedback control using a quadratic cost function for a three machine case. The three machine case is a reduced model of the Scandinavian network obtained from Vattenfall.

Linear quadratic control theory has been applied to the design of a control strategy for the system in

Lindahl, S.: Optimal Control of a Multimachine Power System Model, Report 7211, May, 1972.

This report indicates what results can be achieved if all stations have complete information about the states of all other stations. The control in case of restricted information transfer is currently being investigated.

Paper Machine Control

A graduate course on process control in the paper industry was given during the year. In this course a critical evaluation of models of various parts of a paper machine was given. Different control strategies were also investigated. The conclusions are summarized in

Åström, K.J.: Lecture Notes on Paper Machine Control - Head Box Flow Dynamics and Control. - Dynamics of the Wet End of a Paper Machine. - A Simple Paper Machine Model.

A masters thesis project aimed a more detailed study of the head box models and head box control has also been initiated. Several term papers have also been devoted to various aspects of the paper machine control problem.

We have also collaborated with Mr B. Häggman of Svenska Träforskningsinstitutet (STFI) on modeling and identification of paper machine dynamics. Both steady state non-linear models and linearized small perturbation models have been considered. The experimental studies have been performed on the experimental paper machine at STFI and our parameter estimation programs have been used to obtain appropriate models. Experiments on real systems are also planned.

Thermal Process

A one dimensional heat diffusion process is one of the experimental processes in the laboratory. Problems of identifying and controlling multivariable and infinite dimensional systems are considered. Process inputs are the end temperatures of a long copper rod. Process outputs are the temperatures in seven equally spaced points along the rod. The process is an example of a distributed parameter system.

Identification

Parametric linear single-input single-output discrete models are determined using the maximum likelihood method. A theoretical model of the process is given by the infinite partial fraction expansion of the transfer function

$$G(x,s) = \sum_{k=1}^{\infty} K_k(x)/(1+T_k s) \qquad (*)$$

relating the temperature at a point x on the rod to the end temperature. It has been shown that adjacent modes of the model (*) which have gain factors $K_k(x)$ of the same sign are represented by a single mode in the estimated models. The sum of the gain factors of the adjacent modes is the gain factor of the single mode. The modes of the model (*) which are close to the Nyquist frequency $-\pi/T$ are in some cases represented by a pair of complex modes. The estimated models are of 4:th and 5:th orders. The results are reported in

> Leden, B.: Identification of Dynamics of a One Dimensioned Heat Diffusion Process, Report 7121, November, 1971.

Determination of Thermal Diffusivity

Different methods for estimating the thermal diffusivity of the rod have been investigated. The methods considered are a periodic temperature method, an on-line mathematical programming method and a maximum likelihood method.

The periodic temperature method is a classical method and uses a sinusoidal input signal. The thermal diffusivity is computed from measurements of the amplitudes and phases along the rod. Errors in determining the thermal diffusivity are of the order of 1%.

The on-line mathematical programming method approximates the distributed parameter system using finite differences and an error function is obtained. By minimizing the integral of the weighted error squared over an observation interval the required parameters are identified. This method is extremely fast and errors in determining the thermal diffusivity are of the order of 1%.

The maximum likelihood method uses finite differences to approximate the partial differential equation with a 21:st order vector differential equation. The matrix exponential technique is employed to integrate the differential equation. By maximizing the likelihood function the unknown parameters are estimated. This method can handle non piecewise constant input signals and is extremely accurate. Errors in determining the thermal diffusivity are of the order of 0.01%. The errors of methods earlier presented in literature are of the order of 1%.

This study is performed in collaboration with Dr M.H. Hamza, the University of Calgary, Canada, who has done the investigation based on the on-line mathematical programming method. The results clearly show that system identification techniques can be powerful tools for obtaining precise measurements of physical variables

Control

Different algorithms to implement Kalman filters for real time estimation and control have been investigated in

> Källström, C. and Åström,K.J.:Real Time Computing III - Implementing Linear Filtering and Control Algorithms, Report 7122(B), December, 1971.

The algorithms are used to estimate the temperature profile of the rod from measurements of the temperature in discrete points. The end temperatures are thereby subjected to random disturbances. The possibility of detecting failures in individual temperature sensors has been given special attention.

Dead beat strategies based on the identification experiments are also implemented. This study shows that the deterministic models describe the process well.

Economic Systems

It is a current belief among control scientists that many concepts and techniques developed in control theory can be applied to other fields outside engineering. To get some insight a few small studies have been carried out. Some modeling and control problems in economics have been considered. We have thus participated in an informal seminar between control theorists and economists. This is reported in

> Åström, K.J.: National Bureau of Economic Research Workshop on Stochastic Control and Economic Systems, Princeton 1972, Report 7215, May, 1972. (Trip report).

Through contacts with Dr Bray and Professor Westcott we have also been following a project aimed at developing a mathematical model for the UK economy. Our estimation and modeling techniques have been conveniently applied to obtain single equation models. A masters thesis project aimed at analysing a few sectors using our interactive modeling package has been initiated.

Biological Control

The work on biosystems has been intensified. In the master thesis

> Johansson, L.: Inkompatibilitetslocus: Beräkning av allelfrekvenser i en rödklöverpopulation, (Incompatibilities in allele fluctuations in a red clover population), RE-112, July, 1972.

simulations are made of genetic population models commonly used to describe the system for prohibiting self-fertilization in e.g. red clover. The model is non-linear and difficult to analyse by hand. The behavior for high order systems has been totally unknown. Experiments will be performed to show if the model sufficiently describes the actual performence.

Maximum Likelihood identification is applied to workload - heart rate data obtained at The Department of Aviation and Naval Medicin, Karolinska Institutet, Stockholm. Second order systems are obtained with time constants of about 20s and 200s. The results are reported in

> Hagander, P.: Maximum Likelihood Identification of the Workload - Heart Rate Dynamics in man Using PRBS, Report 7208(B), April, 1972.

Other contacts are opened especially concerning the drug-administration problems and a master thesis work is applying linear stochastic control to digitalis dosage, starting with a model obtained at the University of Southern California.

The possibilities to obtain exponential fractions in step-responses have been showed to be small, especially when the starting level is uncertain. Nitrogen elimination data from the Department of Physiology, Lund have been analyzed and new sampling interval and experimental length have been recommended giving better data. The purpose, to show physiologically reasonable parameter changes for different experimental conditions, was however, not possible to reach. The data probably contains a whole spectrum of time constants corresponding to different tissues. The number of fractions that can be identified with any significance are only two or three, each representing an aggregate of fractions. For different experimental conditions the aggregation might be different, so that the amount of nitrogen in the compartments could change, an unphysiological effect, if the compartments were to correspond to certain tissues.

In a master thesis work the balancing capability is analyzed on line using the PDP-15. Spectral analysis, regression analysis and Maximum Likelihood analysis are performed on data from normal people and people subjected to treatment like alcohol and hard work or suffering from different types of diseases. The work is done in collaboration with the Neurological Clinic, Lund.

Miscellaneous

The choice of sampling rates in a digital control system is discussed in

> Nilsson, A. and Nilsson, B.: Digital reglering med processdator, (Digital Control using a Process Computer), Report RE-96, August, 1971.

The results are illustrated by experiments performed in the real time computing laboratory using the electromechanical servo.

An eigenvalue analysis of an autopilot has been done in collaboration with SAAB, Linköping. The results are found in

> Anderini, K.: Studier av digitaliserade ytterloopsfunktioner vid automatstyrning av flygplan, (Studies of digitized outerloops of an Airplane Autopilot), Report RE-98, October, 1971.

An investigation of reconstruction of statevariables versus direct measurements has been done in

Wallin, U. and Widström, A.: Jämförelse mellan störningskänslighet vid direkt mätning och rekonstruktion, (Comparison of direct Measurement and Statevariable Reconstruction), Report RE-105, February, 1972.

Kalman filtering has been compared with the complimentary filtering scheme devised by B. Sjöberg of SAAB in

Karlsson, B. and Skoglund, G.: Jämförelse mellan Kalman- och komplementär filtrering, (Comparison between Kalman Filtering and Complementary Filtering), Report RE-100, November, 1971.

A pressure regulating system in a food processing machine has been studied in a joint masters project with Alfa Laval AB. A theoretical analysis and a pilotplant study is reported in

Sundström, K.: Stabilitetsundersökning av Trycksimulator, (Investigation of the Stability of a Pilot Plant Pressurizer), Report RE-99, October 1971.

The problem of controlling the current in a welding arc using thyristors has been studied in collaboration with AGA AB. The problem turned out to be an interesting application of sampled data theory. The results are found in

Janiec, M.: Styrning av ljusbåge med tyristorer, (Control of a welding arc using thyristors), Report RE-109, June, 1972

A joint project with SUPRA, Landskrona aims at better control of a granulator in a fertilizer plant. Dynamic experiments have been performed and the modelling work is initiated.

A joint study with LKAB, Kiruna through R. Syding is devoted to control of an ore crusher. Parts of the system are modeled. Simulation studies indicate an application for a self tuning regulator.

Dynamics experiments on a cement mill have been done jointly with AB Cementa in Limhamn. The results are given in

> Nilsson, R.: Modell av malkvarn, (Modelling of a grinding mill), Report RE-106, March, 1972.

7. SYSTEM THEORY

The introduction of the graduate program has made it possible for us to broaden the scope of the research. A result of this is a research activity in system theory.

Linear System Theory

The relations between the Riccati equation and invertibility is discussed in

> Hagander, P.: Inversion of a Dynamical System by an Operator Identity, Automatica 8, (1972), 361-362.

Operator formulation of the discrete estimation problem has also given a neat derivation of the formulas for the smoothing problem. It is reported in

> Hagander, P.: Smoothing for discrete time Systems using Operator Factorization, Report 7214(B), July 1972.

As an application of the duality between linear estimation and linear quadratic control a new result is obtained concerning the start up of a Kalman filter from unknown initial values. A report is under preparation.

Multivariable Systems

The generalization of PI-regulators to multivariable systems has been completed. In the case of constant disturbances, simple algorithms have been developed to design low order proportional and integral controllers. Simulations have shown that efficient PI-controllers can be designed in this way.

The question of identifiability of linear multivariable systems has turned out to be a difficult problem to solve at least in the global case. Some sufficient conditions for local and global identifiability have been derived. In the latter case, the applicability of the results is, however, rather restricitve.

Some new work has started on synthesis of controls with predefined configurations or information sets. This kind of problems have turned out to have relevance for example in control of power systems. In fact existing control theory gives very few result that can be applied in practice to problems of this kind. One relevant problem within this area is the following

> Given a state feedback control, can we find some feedback with a predefined structure that in some sense "approximates" the state feedback.

Computationally efficient methods to do such "approximations" have been developed and a computer program has also been written for this purpose.

An IFAC Congress on "Multivariable Technical Control Systems" was held in Düsseldorf, October 1971. The Institute was represented by civ ing Gunnar Bengtsson. A presentation of the contributions at the Congress along with some general comments are given in a travel report.

Three reports, covering the work that has been done within the area of multivariable control system, are just under preparation.

8. TECHNOLOGY ASSESSMENT

It may be of interest to users to know the status of the results and to have some indication of the fields of applicability. An attempt to provide this is given below. It is hoped that it can contribute towards further interactions between our research and potential users.

System Identification

Many programs and much experience from analysis of real data exist. The results are believed to be applicable not only to technical processes but also to modeling of economic and biological systems. The system identification techniques can provide

- Reasonable control models even when models based on physical equations are very complex. Experience has shown that low order models are frequently sufficient.

- Models for disturbances which cannot be obtained by other means. A characterization of disturbances is of course very important for the design of control strategies.

- New or alternative methods for measuring important physical parameters. Typical examples are the determination of hydrodynamic derivatives and the measurement of heat diffusivity mentioned in Section 2.

Adaptive Systems

It is believed that the self tuning regulators developed can have many applications. Laboratory experiments have indicated the feasibility of algorithms for systems with feed-forward loops and multivariable systems. The existence of a flexible interactive simulator makes it easy to do a feasibility study for a particular example. Preliminary experiments in industrial environment have been promising.

The potentials to provide automatic tuning of regulators are important to a large number of industrial applications, particularly since the self tuning algorithms have very modest storage and computing requirements. A straight forward FORTRAN program for the simple version STURE 1 requires a code consisting of 450 memory locations on the PDP 15/30. Eight parameters can be tuned in about 70 ms per iteration.

Computational Control

The access to a well documented software library has a significant impact both on research and education, by providing practitioners of automatic control with powerful tools. Experience has shown that tasks that previously required an effort of the order of a master thesis (3 man months) can now be carried out in about two man weeks. The availability of interactive packages like SYNPAC and SIMNON will most likely contribute significantly towards a more wide spread use of the tools of modern control theory. As a typical case we can quote experience from a course in system techniques for mechanical engineers. After one two hours lecture on linear quadratic control theory the students were able to design good regulators for multivariable boiler control by using SYNPAC.

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Hagander, P.: A Numerical Solution of $A^TS + SA + Q = 0$, Information Sciences 4 (1972), 35-50.

Hagander, P.: Inversion of a Dynamical System by an Operator Identity, Automatica 8 (1972), 361-362.

Olsson, G.: Power - Nuclear Plants, Commentators Report 5th IFAC Congress, Paris, June, 1972.

APPENIDX C

TECHNICAL REPORTS

Report 7108 (B)	Borisson, U. and Holst, J.: Real Time Computing II Minimal Variance Control on Process Computer, September, 1971.
Report 7109 (B)	Hagander, P.: Inversion of a Dynamical System by an Operator Identity, September, 1971.
Report 7110	Wittenmark, B.: A Survey of Adaptive Control Methods, September, 1971.
Report 7111	Wieslander, J.: Real-Time Identification Part II, September, 1971.
Report 7114	Hagander, P.: Linear Control and Estimation using Operator Factorization, July, 1971.
Report 7115	Åström, K.J.: Final Report for Project Process Control 1970 - 1971. Contract 70-337/U270 Swedish Board for Technical Development. September, 1971.
Report 7116 (B)	Åström, K.J.: Modeling and Identification of Power System Components, October, 1971.
Report 7118	Lindahl, S.: A State Space Model of a Multi-machine Power System, November, 1971.
Report 7119	Ljung, L.: Characterization of the Concept of 'Persistently Exciting' in the Frequency Domain, November, 1971.
Report 7120	Wittenmark, B.: Master Thesis in Automatic Control 70/71. (Examensarbeten), November, 1971.

Report 7121	Leden, B.: Identification of Dynamics of a one Dimensional Heat Diffusion Process, November, 1971.
Report 7122	Källström, C. and Åström, K.J.: Real Time Computing III Implementing Linear Filtering and Control Algorithms, December, 1971.
Report 7201	Hagander, P.: Numerical Solution of $A^TS + SA + Q = 0$†
Report 7202	Källström, C. and Åström K.J.: Identification and Modelling of Ship Dynamics.
Report 7203	Wieslander, J. and Wittenmark, B.: An Approach to Adaptive Control Using Real Time Identification.
Report 7204	Åström, K.J. and Eykhoff, P.: System Identification - A Survey.
Report 7205 (B)	Ljung, L.: Cykeln som Dynamiskt System
Report 7206	Mårtensson, K.: New Approaches of the Numerical Solution of Optimal Control Problems.
Report 7207 (B)	Olsson, G.: Maximum Likelihood Identification of some Loops of the Halden Boiling Water Reactor.
Report 7208 (B)	Hagander, P.: ML Identification of Workload-heart Rate Dynamics in Man Using PRBS.
Report 7209	Åström, K.J. and Wittenmark,B.: On Self-Tuning Regulators.
Report 7210	Lindahl, S. and Ljung, L.: Identification of Power Generator Dynamics from Normal Operating Data.

Report 7211 Lindahl, S.: Optimal Control of Multimachine Power System Model.

Report 7212 Gustavsson, I.: Comparison of Different Methods dor Identification of Industrial Processes.

Report 7213 (B) Wittenmark, B., Lindahl, S. and Sternby, J.: Systemteknik, Projektarbeten 1972. Ångpanne-reglering, kraftsystem, produktionsplanering.

Report 7214 (B) Hagander, P.: Smoothing for Discrete Time Systems using Operator Factorization.

Report 7215 (B) Åström, K.J.: National Bureau of Economic Research Workshop on Stochastic Control and Economic Systems, Princeton 1972.

Report 7216 (B) Åström, K.J.: Besök på Case Western Reserve University den 1 - 3 Maj, 1972.

Report 7217 (B) Åström, K.J.: Linear Sampled Systems with Time Delay which is a Fraction of the Sampling Period.

APPENDIX D

MS THESES

RE-96 Nilsson, A., Nilsson, R.: Digital Reglering med processdator (Digital Control Using Process Computer) August 1971.

RE-97 Bosrup, L., Gustavi, J-O.: Självlärande klassificering. (Self-learning classification) September 1971.

RE-98 Anderini, K.: Studier av digitaliserande ytterkoopsfunktioner vid automatstyrning av flygplan (Studies of Digitized Outerloops of an Airplane Autopilot) October 1971.

RE-99 Sundström, K.: Stabilitetsundersökning av trycksimulator (Investigation of the Stability of a Pilot Plant Pressurizer) October 1971.

RE-100 Karlsson, B., Skoglund, G.: Jämförelse mellan Kalman och komplementär filtrering (Comparison between Kalman and Complementary Filters) November 1971.

RE-101 Lindell, J.O.: Plotterrutiner för PDP-15 (Plottering Routines for PDP-15) October 1971.

RE-102 Andersson, P.O., Olofsson, T.: Undersökning av Marsiks adaptiva regulator (Investigation of Marsik's Adaptive Controller) December 1971.

RE-103 Almqvist, R.: Program för Maximum Likelihood identifiering på PDP-15 (Programs for Maximum Likelihood Identification on PDP-15) February 1972.

RE-104 Novén, T.: SYNPAC - Ett interaktivt program för syntes av reglersystem (SYNPAC - An Interactive Program for Synthesis of Control Systems) February 1972.

RE-105 Wallin, U., Widström, A.: Jämförelse mellan störningskänslighet vid direkt mätning och rekonstruktion (Comparison of Direct Measurement and Statevariable Reconstruction) February 1972.

RE-106 Nilsson, R.: Modell av malkvarn (Modelling of a Grinding Mill) March 1972.

RE-107 Ericsson, S., Lindquist, H.: Statistisk Signalklassificering utan lärare (Statistic Classification without Teacher) April 1972.

RE-108 Nilsson, L.O.: Optimal Styrning av Sulfitkokare (Optimal Control of a Sulphite Digester) April 1972.

RE-109 Janiec, M.: Styrning av Ljusbåge med Tyristorer (Control of a Welding Arc using Tyristors) June 1972.

RE-110 Pernebo, L.: Adaptiv Styrning av Linjära System med Hjälp av utvidgat Kalmanfilter (Adaptive Control using Extended Kalman Filter) August 1972.

RE-111 Carlsson, S.: Maximum Likelihood Identifiering av reaktordynamik från flervariabla experiment (ML Identification of Reactor Dynamics from Multivariable Experiments) June 1972.

RE-112 Johansson, L.: Inkompatibilitetslocus. Beräkning av allelfrekvenser i en rödklöverpopulation (Incompatibilities in allele fluctuations in a red clover population) July 1972

RE-113 Elmqvist, H.: SIMNON - Ett interaktivt simuleringsprogram för olinjära system (SIMNON - An interactive Program for Simulating Non-linear Systems) June 1972.

COURSES AND SEMINARS

The courses and seminars given are summarized in this appendix.

Courses

The following courses have been given by invited lecturers in cooperation with other departments at the University and by the personnel at the Division.

Optimal Control	Div. of Automatic Control
Real Time Computers	Div. of Automatic Control
Survey Course	Div. of Automatic Control
Process Control	Div. of Automatic Control in connection with invited lecturers from the swedish paper industry
Stochastic Processes	Div. of Mathematical Statistics
Differential Dynamic programming	Div. of Automatic Control

Seminars

Invited Swedish and Foreign lecturers have contributed with the following seminars.

Mrs M. Molnar, Automation Research Institute of the Hungarian Academy of Sciences, Budapest.

"Computer Control System for an Ammonia Plant in Hungary", November 19, 1971.

Mr V.H. Pedersen, DTH, Köpenhamn.

"Computer Aided Design of Drying Plants", November 19, 1971.

K. Smuk, Czechoslovakien Academy of Sciences, Czech-Slovakia.

"Nekolny - Algorithms", November 24, 1971

Mr Mats Rudemo, FOA, Stockholm.

"Tillståndsestimering för partiellt observerade markovkedjor", (State Estimation of Partially observed Markov Chains). December 3, 1971.

Mr G. Fick, FOA, Stockholm.

"Integrationsrutin för system av ordinära differentialekvationer som får innehålla diskontinuiteter", (Integration Routine for Systems of Ordinary Differential Equations that may Contain Discontinuities), December 8, 1971.

Mr A. Holvid, KTH, Stockholm.

"Matematisk programmering", (Mathematical Programming), December 9, 1971.

Professor J.D. Schoeffler, Case Western Reserve University, Cleveland, Ohio.

"Survey of Hardware and Software for Process Control", January 10, 1972.

"Real Time Languages for Process Control", January 11, 1972.

"Template Macro Assemblers and their Applications", January 13, 1972.

"Software Organization for Multi-Computer Process Control", January 14, 1972.

"Contingency Control", January 18, 1972.

Dr J. Kohlas, Brown Boveri, Schweiz.

"Maximum Likelihood Methods in the Identification of Dynamical Systems", January 17, 1972.

Dr Handschin, Brown Boveri, Schweiz.

"State Estimation in Power Systems", January 17, 1972.

Dr L.E. Torelli, KTH, Stockholm.

"Interaktiva språk", (Interactive Languages), February 11, 1972.

Mr A. MacLean, Saab-Scania, Linköping.

"Digitala simuleringsspråk", (Digital Simulation Languages), February 18, 1972.

Mr G. Malmberg and Mr B. Skarman, Saab-Scania, Linköping.

"Höjdstyrning av robot. En tillämpning av linjärkvadratisk teori", (Height Control of a Missile. An Application of Linear Quadratic Control Theory).

Mr P.O. Lidby, Iggesund.

"En processteknikers syn på pappersindustrins reglerproblem", (A Process Technician's view on Control Problems in the Paper Industry), March 2, 1972.

Mr G. Bolin, SCA, Sundsvall.

"Några praktiska synpunkter på pappersindustrins reglerproblem", (Some Practical Aspects on Control Problems in the Paper Industry), March 22, 1972.

Professor D. Wahren,

"En pappersmakares syn på reglerproblem inom pappersindustrin", (A Paper Maker's view on Control Problems in the Paper Industry), March 24, 1972.

Professor O.A. Asbjørnsen, NTH, Trondheim, Norge.

"Termodynamiska tillståndsvariabler", (Termodynamical state variables), May 2, 1972.

"Homogena system. Fundamentala ekvationer för kemiska reaktorer I", (Homogenous Systems. Fundamental Equations for Chemical Reactors I), May 3, 1972.

"Homogena system. Fundamentala ekvationer för kemiska reaktorer II", (Homogenous Systems. Fundamental Equations for Chemical Reactors II), May 4, 1972.

"Heterogena system. Dynamik hos destillationskolonner och gasabsorption I", (Heterogenous Systems. Dynamics of Destillation Columns and Gasabsorption I).

"Heterogena system. Dynamik hos destillationskolonner och gasabsorption II", (Heterogenous Systems. Dynamics of Destillations Columns and Gasabsorption II).

Professor R. Bellman, Univ. of Southern California, Berkeley.

"Mathematics and Cancer". May 8, 1972.

Professor W.M. Wonham, Univ. of Toronto, Canada.

"Regulation and Internal Stabilization in Linear Multivarialbe Systems", June 1, 1972.

Dr R.P. King, South Africa.

"Modeling of Random Phenomena in Chemical and Metalurgical Equipments", June 6, 1972.

Dr A. Lindqvist, KTH, Stockholm.

Dr Lindqvist visited the Division during May and June 1972. He gave a lecture series on the subject "Optimal Control of Linear Stochastic Systems", based on Dr Lindquist's Ph.D. thesis. Dr Lindquist has extended the ordinary linear filtering theory to include also systems with time delays.

Professor M. Aoki, Univ. of California.

Professor Aoki visited the Division during May 1972 and gave a series of lectures on "Informationally Decentralized Systems".

He considered the problem of controlling systems where the different "control agents" have different information about the total system. Problems of this kind often occur in large-scale system. Professor Aoki showed how algebraic and geometric methods can be used to stabilize and optimize such systems.

Professor P. Falb, Brown University, Providence.

Professor Falb visited the Division in June 1972 and held a seminar series on the subject "Solution of Two Point Boundary Value Problems".

Professor Falb considered non-linear systems of the form

$$\dot{x} = f(x,u,p) \qquad x(0) = x_0$$

$$\dot{p} = g(x,u,p) \qquad p(T) = p_1$$

This kind of equations often occur in optimal control theory. By rewriting the system in the form of an integral equation with a linear part, professor Falb was able to give as well existance theorems as numerical algorithms for the solution.

Professor J. Breakwell, Stanford University

"The Homicidal Chauffeaur".

Professor Breakwell discussed a particular problem of differential games where many features of the optimal strategy could be obtained by a combination of analysis and computation.

Kontaktsekretariatet
Tekniska Högskolan i Lund
Fack
220 07 LUND 7

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Syftet med kontaktdagarna är

- att skapa ett diskussionsforum för och informationsutbyte mellan användare av smådatorer
- att ge en överblick över dagsläge och trender vad beträffar programvara för smådatorer
- att informera om STU:s stöd till processreglering
- att informera om pågående forskning vid Institutionen för Reglerteknik vid LTH

Huvudvikten under mötets första del lägges vid industriella problem i samband med datainsamling, mätvärdesbearbetning och styrning med dator. Ett antal representanter för olika branscher kommer att delgiva sina erfarenheter av projektuppläggning, val av dator, installation, programuppläggning, drift och reglering. Syftet är att försöka finna, dels var de största svårigheterna ligger, dels i hur hög grad gemensamma problem för olika branscher uppträder. Under symposiets andra del ligger betoningen på information om institutionens forskningsverksamhet.

Upplysningar

om programmet genom Gustaf Olsson, tel. 046/12 46 00, ankn. 1504

om övrigt genom Kontaktsekretariatet, Ann-Britt Madsen, tel. 046/12 46 00, ankn. 1010

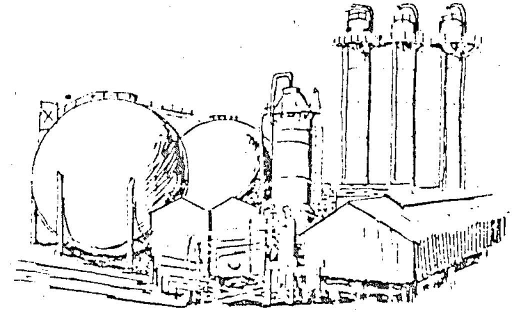
Ledare för kontaktdagarna: Prof. Karl Johan Åström, Inst. för Reglerteknik, LTH

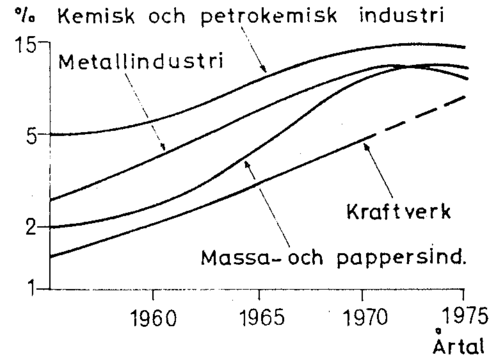
Tider:	Torsdag 18 maj kl 10.00—Fredag 19 maj kl 16.30
Lokal:	Hörsal B, Maskinhuset, Ole Römers väg 1, Lunds Tekniska Högskola
Avgift:	250:— inbetalas på Lunds Universitets postgirokonto 1 56 50 - 5. Märk talongen "Processreglerings-dagar"
Anmälan:	Genom insändande av bifogad kupong eller per tel. tel. 046/12 46 00, ankn. 1010 före den 5 maj 1972. Deltagarantalet är begränsat.
Hotellrum:	Varje deltagare får själv beställa hotellrum. Ett begränsat antal rum är reserverade på Hotell Lundia (046/12 41 40) och på Grand Hotell i Lund (046/11 70 10)
Måltider:	Lunch och kaffe torsdag och fredag ingår i priset. På torsdag kväll göres en utflykt med buss till Svaneholms slott, där middag serveras. Middag ingår i priset.

Bildtext:

Kostnad för processtyrning inom olika industrigrenar enligt amerikanska undersökningar. Diagrammet hämtat ur Elektronik Specialnummer 1970 sid. 39.

WALLIN & DALHOLM BOKTR. AB, LUND





LTH och STU inbjuder till

PROCESS REGLERINGS DAGAR

LUND

18—19 maj 1972

APPENDIX F

Program

torsdag den 18 maj

SMÅDATORER OCH PROCESS-REGLERING

STU:s STÖD TILL PROCESSREGLERING
Övering. Sigvard Tomner, Styrelsen för Teknisk Utveckling

PRESENTATION AV MÖTESPROGRAMMET
Univ.lektor Gustaf Olsson, LTH

SAMVERKAN UNIVERSITET — INDUSTRI
Professor Karl Johan Åström, LTH

PROGRAMVARA FÖR SMÅDATORER — DAGSLÄGE OCH UTVECKLINGSTENDENSER
Tekn. lic. Johan Wieslander, LTH

INDUSTRIELLA PROCESSDATOR-PROBLEM

REGLEPROBLEM I ALUMINIUMVERK
Professor Birger Qvarnström, Inst. för Reglerteknik, Chalmers Tekn. högskola

IDÉER OCH ARGUMENT BAKOM IGGESUNDS PROCESSDATORPROJEKT
Övering. P. O. Lidby, Iggesunds AB

INSTALLATIONSPROBLEM FÖR DATORER I MILJÖ MED TUNG HANTERING
Civ.ing. Lennart Swahn ASEA-LME Automation

SMÅ PROCESSDATORER I STÅLINDUSTRIN
Tekn. Dr. Karl Eklund, Axel Johnson Institutet för Industriforskning

DATORSTYRNING I TURBINTANKERS
Civ.ing. Johannes Eriksson, Civ.ing. Leif Steen, Kockums Mek. Verkstad

Program

fredag den 19 maj

INDUSTRIELLA PROCESSDATOR-PROBLEM (forts)

UPPLÄGGNING AV PROCESSDATORPROJEKT VID ALFA-LAVAL
Tekn. lic. Jan Hälldin, Alfa-Laval

UTBYGGNADSETAPP 2 I GULLFIBERS PROCESS-DATORPROJEKT
Ing. Alf Eriksson, Gullfiber AB

PROCESSREGLERING SOM INSTRUMENT I MILJÖVÅRDEN – MÖJLIGHETER OCH FÖRVÄNTNINGAR
Tekn. lic. Ragnar Alberg, Gullfiber AB

PANELDISKUSSION

PRESENTATION AV FORSKNING VID LTH

MODELLBYGGE OCH PROCESSIDENTIFIERING
Tekn. lic. Ivar Gustavsson, LTH

SJÄLVINSTÄLLANDE REGULATORER
Tekn. lic. Björn Wittenmark, LTH

DATORSTÖDD DIMENSIONERING AV REGLER-SYSTEM
Tekn. lic. Johan Wieslander, LTH

VISNING AV INSTITUTIONENS PROCESSDATOR

OPTIMERINGSMETODER
Tekn. lic. Krister Mårtensson, LTH

MODELLER FÖR ÅNGKRAFTVERK
Tekn. Dr. Karl Eklund, Axel Johnson Institutet för Industriforskning

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Jag anmäler mig till
Processregleringsdagar 18—19 maj 1972
vid Institutionen för Reglerteknik, Tekniska Högskolan i Lund

Titel och namn ______________________

Företag eller institution ______________________

Adress ______________________

Postnr och postadress ______________________

Avgiften för deltagande, 250 kr, torde inbetalas på postgiro 1 56 50 - 5,
Lunds Universitet, Fack, 221 01 LUND 1
Var god angiv på talongen: "Processregleringsdagar"

APPENDIX G

LECTURES

The staff of the institute have given several outside lectures and seminars during the year. The most important ones are listed below.

1. "Topics of Stochastic Control Theory". Lecture by K.J. Åström at the Institute of Information Theory, Prague, September 7, 1971.

2. "Modelling and Identification of Power System Components". Brown Boveri Symposium on Real Time Control of Electric Power Systems, Baden, September 27, 1971.

3. "Processdatorer i Industri". K.J. Åsrröm
   "Karakterisering av Reglerproblem". B. Wittenmark
   "Representation av Processer och Störningar". Ivar Gustavsson
   "Modellbygge". Karl Eklund
   "Stationär reglering". Per Hagander
   "Statisk och dynamisk optimering. Omställning". Krister Mårtensson
   "Systemuppbyggnad". Johan Wieslander
   "Krav på systemet". Sture Lindahl
   "Realiserbarhet". Johan Wieslander
   "Specifikation och utvärdering av processdatorer". Gustaf Olsson.
   Lectures given at Skövde, 12 - 15 October, 1971.

4. "Identification and Modelling of Industrial Processes". K.J. Åström, Colleque Contrôle des Procédés, IRIA, Paris October 18, 1971.

5. "Modern Reglerteori - Användbart Verktyg eller Akademisk Svartkonst" Lecture by B. Wittenmark to Elektriska Klubben, Västerås, November 10, 1971.

6. "Några Erfarenheter av Samarbete med Näringslivet vid Institutionen för Reglerteknik, LTH". Lecture by K.J. Åström to Regional IVA Meeting, Malmö, January 19, 1972.

7. "Reglerteknik och Pappersindustri". Lecture by K.J. Åström to the SPCI's Ekmandagarna, January 25, 1972.

8. "Datorer som Regulatorer" and "Datorstödd Dimensionering av Reglersystem" Lecture and demonstration by K.J. Åström and Johan Wieslander to the SSI Conference about Information system and processreglering, Lund, April 19, 1972.

9. "Modellbygge, Identifiering och styrning av kraftsystem" and "Reglerteknik i kraftindustrin" Lectures by S. Lindahl and G. Olsson for AB Atomenergi, April 27, 1972.

10. "On Self-tuning Regulators" Lecture by K.J. Åström at Case Western Reserve University meeting on control of complex systems, Cleveland, Ohio, May 3, 1972.

11. "Identification and adjoint problems of process computer control" Lecture by G. Olsson at Enlarged Halden group meeting Loen, May 29, 1972.

12. "Adaptive Control and Self-tuning Regulators" Lecture by K.J. Åström, Technical University in Twente, Holland, May 30, 1972.