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# PROCESS CONTROL 1972-1973

# FINAL REPORT

PROJECT 72-202/U137

SWEDISH BOARD FOR TECHNICAL DEVELOPMENT

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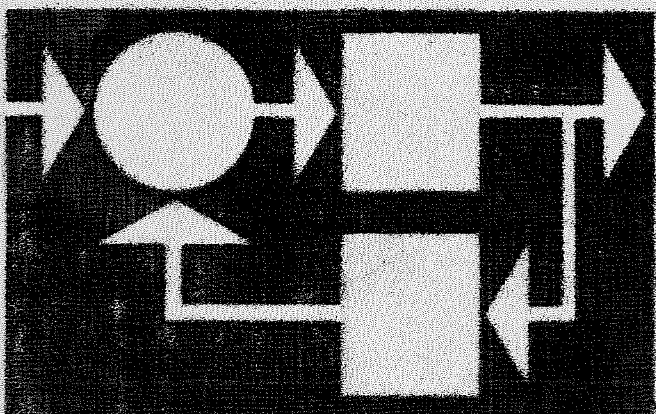

REPORT 7329 september 1973

LUND INSTITUTE OF TECHNOLOGY
DIVISION OF AUTOMATIC CONTROL

ABSTRACT

This report gives a survey of the results achieved at the Division of Automatic Control during the year 1972 - 1973. Most of the research has been centered around the Process Control Project. The project contains system identification, computational control, real time computing, adaptive control, system theory, non-technical systems and applications. During the year 19 published papers and 44 technical reports have been written. Two PhD theses, one licentiat thesis and 18 MS-theses have also been completed.

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# 1. INTRODUCTION

A long range program in the area of process control /1/ has now been completed. Partial results of the progress have been reported in /2/, /3/, /4/, /5/ and /7/.

Most of the research at the Division of Automatic Control has been centered around the process control project. Except the research engineers directly supported by the Swedish Board for Technical Development (STU) students and staff members of the Institute have given support and contributions to the research. The research program has been continued in four main areas with one research engineer responsible as project leader for each activity. The projects are System Identification (Ivar Gustavsson), Computational Control (Krister Mårtensson, Claes Källström), Real-Time Computing (Johan Wieslander). A research project, supported separately by STU, has been undertaken on self-tuning regulators. Björn Wittenmark has been responsible for that project. Another application area "Control systems in climatized buildings" (Lars Jensen) has been supported by the National Swedish Board of Building research.

It has been possible to continue the rewarding collaboration with industries and other research institutions on applications of different process control theories. These results are also reported here.

The real time computer installation has more and more proven to be a significant tool for most of the activities. Much progress is a result of a powerful software and hardware configuration. Programs for interactive design of control systems have been extensively used and interactive model building is considered as a most elegant and efficient tool. This work will continue with more emphasis for the coming years.

The laboratory processes have been connected to the process computer and new algorithms have been tested in real time environment. An even more interesting feature is the connections between the process computer and full scale industrial plants over the public telephone network. In this way advanced control algorithms have been tested in full scale successfully with a remarkably little investment in manpower and money.

The real time computer has been used for about 6000 hours during the last year.

The interaction between the graduate program and the research projects is considered important. In this way an amplification effect of the results has been achieved in the sense, that PhD projects and graduate courses have supported the main projects of the research. During the year two PhD theses have been completed as well as one licentiat thesis and 18 MS-theses.

In collaboration with Mr K. Anvret of Svenska Teknologföreningen a course "Automatic Control-Current Theory" has been given for industrial people. Several staff members have also given other lectures or presented papers at meetings and conferences. Especially the IFAC Symposium in the Hague on Identification and System Parameter Estimation should be mentioned. One invited survey paper, one case study, one tutorial and six full papers were presented there by members of the Division.

## 2. SYSTEM IDENTIFICATION

During the last 6 years System Identification has been one of the main parts of the process control research at the Division. New methods have been developed and studied. Different methods have been compared. In connection to this an identification program package has been built up. The different methods have also been applied to a great number of industrial processes as well as e.g. biological and economical systems. Earlier results are reported in /2/, /3/, /4/,/5/ and /7/.

The research on system identification at the Division is considered to be at a high international level. This was made obvious at the 3rd IFAC Symposium on Identification and System Parameter Estimation in the Hague, 1973. Out of 11 invited survey papers and case studies one survey paper, Gustavsson (paper 1973) and one case study, Eklund and Gustavsson (paper 1973) were presented from the Division. Furthermore professor K.J. Åström gave a tutorial on Maximum Likelihood identification. Of 68 full papers 6 came from the Division. Two of them were written in collaboration with other institutes. Three of the papers were presented at the theoretically oriented sessions, Peterka and Åström (paper 1973), Hamza, Leden and Sheirah (paper 1973) and Söderström (paper 1973a). The other three papers were presented at the practically oriented sessions, Åström and Källström (paper 1973a), Lindahl and Ljung (paper 1973) and Olsson (paper 1973). It was obvious that these contributions received much attention and the interest in our activities, e.g. our program facilities, was immense. We also contributed to one of the test cases which were designed in order to unify comparisons between different methods, Nilsson (report 7321(C)).

The project System Identification is now finished. The great number of papers at the IFAC Symposium can be considered as one form of summing up. In addition a great number of papers, reports and theses have been published on the subject. We have now a deep understanding of the problems, particularly for single input single output linear time invariant systems. There is also a large program library and an extensive experience in identification of different kinds of real processes. In the paper by Gustavsson (paper 1973) a survey of applications of identification to chemical and physical processes is given. The paper includes a review of actual applications in these fields and a discussion of practical identification problems. In different new research projects some of the work will be continued and extended. Identification of multivariable systems will be considered in more detail. The interactive identification program package for the PDP-15 computer will be developed further. Furthermore identification will be used as a routine procedure in projects where modelling from experiments is necessary.

In the following the work during the last year will be reviewed. The first section presents mainly the theoretical contributions. In the second section a short description of new program facilities is given, and in the last section short references are given to chapter 7 where the applications are described in more detail.

## 2.1 Theoretical problems

A PhD thesis mainly dealing with the uniqueness of Maximum Likelihood identification for different structures has been finished, Söderström (report 7314). Consistency and identifiability properties have also been studied. A recursive approximative Maximum Likelihood identification algorithm has been investigated. Further comparisons between different methods have been made. A part of this is our participation in one of the test cases for the IFAC Symposium in the Hague 1973.

### Uniqueness of Maximum Likelihood identification for different structures.

The Maximum Likelihood identification method is in practice implemented as minimization of a loss function. Since a search routine must be used for a numerical solution it is possible that it stops in a local minimum point, which is not contemporary a global minimum point. The local minimum points of the loss function have been examined for a number of different structures. In order to get results which are related to the structure only, it is assumed that the data are governed by an equation of correct structure. Of the same reason an asymptotic expression of the loss function, assuming an infinite number of data, is used. A summary of the results are given in Söderström (report 7314).

It has been proved that a version of the Generalized Least Squares method can be interpreted as the Maximum Likelihood method applied to a special structure. For this structure it is proved that the number of local minimum points depends on the signal to noise ratio. For real data it has been found that the loss function can have more than one local minimum point. Figure 2.1 illustrates this experience. The data are obtained from measurements on a distillation column. Model 1, which corresponds to the smallest value of the loss function, gives a good description of the dynamics of the process. In model 2 the main characteristics of the output is interpreted as due to the noise. The results on the Generalized Least Squares method are reported in Söderström (report 7228) and in an abbreviated version in Söderström (paper 1973a).

Time series modelled as an auto-regressive moving average process are treated in Åström - Söderström (report 7306). The main result is that all stationary points are global minimum points. Provided the number of parameters is chosen in a proper way there is a unique global minimum point.

In Söderström (report 7307) the question of uniqueness is examined for three more structures.

For the structure

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

it is shown that the loss function has a unique local minimum if the signal to noise ratio is either very large or very small.

The loss function for the structure

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

has quite different properties. It is proved that a sufficient condition for a unique local minimum point is either that $\deg A^*(q^{-1}) = 1$ <u>or</u> that the input signal is white noise. It is possible to construct examples where these conditions are not satisfied, and where more than one local minimum occurs.

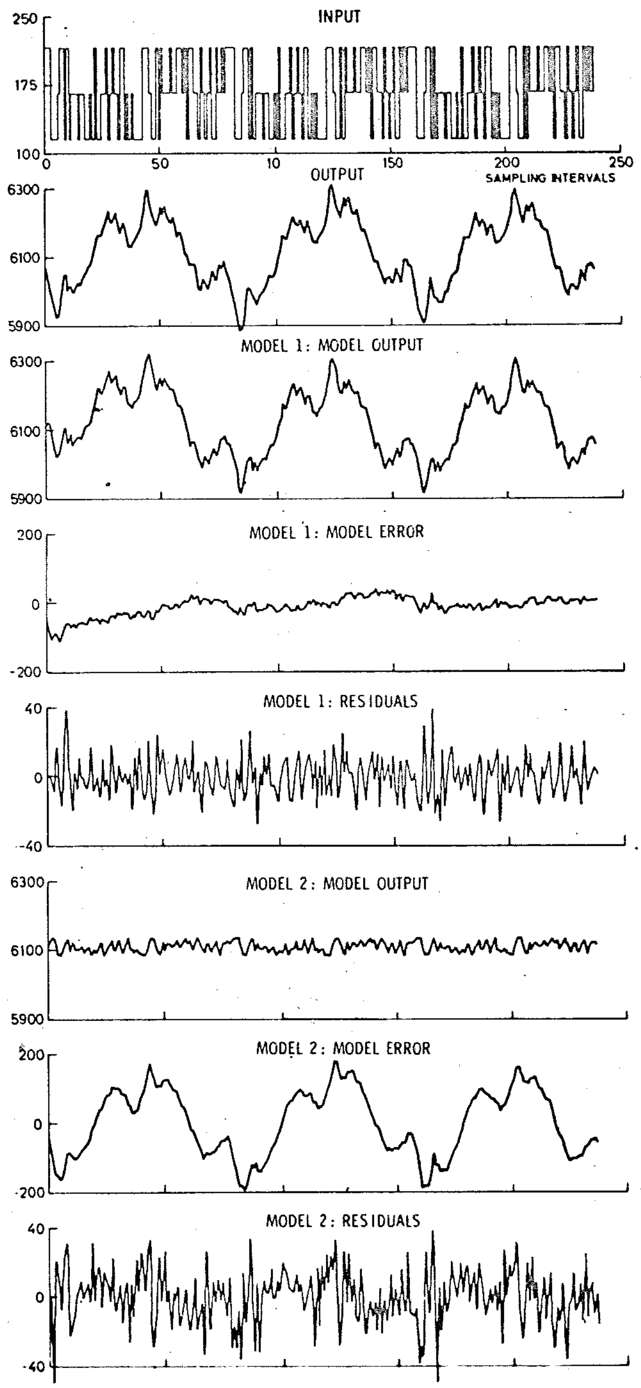
For the more general structure

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

it is shown that first order of the A* polynomial is a sufficient condition for a unique local minimum. The other polynomials can have arbitrary degrees.

Test of common factors in identified models.

The testing of common factors in estimated transfer functions is considered by Burström (MS-thesis RE-124). The test procedure is done in a statistical way. The accuracies of the coefficients of the transfer function are taken into account. Two different ways of treating the problem have been examined. The first one, which also is the superior one, is based on a comparison of the poles and the zeros of the transfer function. The second way is based on the Euclidean algorithm. The two methods are compared using examples obtained from simulated as well as real processes. The results of the first method are generally rather good. The basic drawback of the second method is that the computed test quantities are not reliable.




Models of the distillation column. Digital units are used. The sampling period is 96 seconds.

Figure 2.1 - Demonstration from a distillation column identification that more than one unique model can be found. Model 1 corresponds to the smallest value of the loss function. In Model 2 the main characteristics of the output is interpreted as due to the noise.

## Recursive and real-time identification.

### Recursive Maximum Likelihood identification.

An approximate, recursive version of the Maximum Likelihood method has been developed for the structure

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

The algorithm is described in Söderström (report 7308)

The method has the same degree of complexity as other, well-known recursive identification methods. Comparisons based on simulated examples have been made between the method and the so called Extended Matrix method. It turned out that the proposed method is superior. A condition for a successful application of it is that two "tricks" are used. These consist of repeated restarts and processing of a number of measurements without changing the parameter estimates. These tricks improve the convergence speed and the accuracy considerably.

Later other ways to increase the convergence speed have been examined. It has turned out that a suitable weighting of old measurements gives an improvement of the same kind as the tricks. The report contains application to two real processes as well as to simulated data.

### Suboptimal filters.

In a non-linear system or linear multivariable system with unknown and time varying coefficients it is not possible to construct an optimal recursive identification scheme. It is, however, desirable to find good approximate filters for on-line use.

Jan Holst and Gustaf Olsson have performed a study in order to compare suboptimal filters for parameter estimation.

Three different recursive schemes, all based on Extended Kalman filtering, are tested and compared. Two of the filters are ordinary Extended Kalman filters with different measurement information available. The third filter in addition has an iterative smoothing part. The unknown parameter vector is estimated as part of an extended state vector. The resulting suboptimal filters are tested on linear systems with constant but unknown parameters.

The purpose of the investigation is twofold. As convergence cannot be established generally, this problem has been examined for the test systems. The consistency of the estimates is another problem. Bias and parameter variance are examined and compared to the assumed statistics.

It is shown that the information available when the filtering is performed has a negligable influence on the bias and parameter variance in the long run. However, the artificial noise which has to be assigned to the unknown parameter vector is crucial.

The iterative filter is shown to have a better convergence speed and a larger convergence region then the other filters.

Several numerical problems have arisen in the filter algorithms especially for extremely large errors of the parameter initial values. The origin of these errors as well as methods for avoiding them are also tackled.

Input signal synthesis.

The choice of suitable input signals for identification experiments is an important topic. Works on this subject were reported in last years annual report /7/. The work by Mr L. Keviczky has resulted in a report (report 7226).

## 2.2 Programs.

A considerably improved program package for parameter estimation in linear state space models has been developed for the computer UNIVAC 1108. The ideas behind are briefly presented in Åström - Källström (paper 1973a).

Another program has been developed in order to handle nonlinear systems. Basicly it considers the model

$$\dot{x} = f(x,u,\alpha)$$

$$y = g(x,u,\alpha)$$

where x is the state, y the output, u the input and $\alpha$ the vector of unknown parameters. The model is chosen so that the criterion

$$V = \sum_{t=1}^{N} (y(t) - y_m(t))^T W(y(t) - y_m(t))$$

is minimized with respect to $\alpha$. $y_m$ is the model output, y the real output, W a weighting matrix and N the number of samples. The program has been used to develop a nonlinear model for a drum boiler, Eklund and Gustavsson (paper 1973).

The interactive program for the multiple input single output case on the computer PDP 15 described in last year's annual report /7/ has been improved. Though it includes only some of the most basic facilities it has proved that interactive programs are very efficient tools for process identification. The program package has already been used in several applications.

Programs for the process computer PDP 15 have been developed for the determination of the transfer function of a process using frequency response analysis, Persson (MS Thesis, RE-122). From the teletype it is possible to give desired frequency interval, measuring time etc. The computer then generates sinusoidal waves, measures the output from the system and computes the gain and phase angle. The result is plotted on the display. It is also possible to generate asymptotes and theoretical Bode diagrams for comparison with the measured ones.

## 2.3 Applications.

The available programs for identification and process parameter estimation have been used extensively for modelling of a great number of different processes. We have also been involved in the planning of several identification experiments. In the following the most important applications are reviewed briefly. The applications are described in more detail in chapter 7.

Identification of nonlinear models for drum boiler has been performed using the same data which has been used for the previous identifications of linear models, see Eklund - Gustavsson (paper 1973). Measurements from a gas turbine are now available and used for dynamic modelling. The work on modelling of nuclear reactors has been continued. Both time invariant multivariable models and time varying models have been developed, see Olsson (paper 1973).

An extensive study of paper machine dynamics in which the Division has participated has been performed at the STFI (Svenska Träforskningsinstitutet), Stockholm. The work has resulted in a licentiat thesis by B. Häggman (report 1973 e-i).

A feasibility study on control problems in wastewater treatment plants has been performed during the spring and summer

1973 together with several other institutions (See chapter 7). Within the study identification experiments have been performed at Sjölunda wastewater treatment plant in Malmö. Data from Malmö as well as from Systems Control Inc., Palo Alto, California has been analyzed in an MS-thesis.

A joint study on dynamical problems in a fertilizer plant at Supra, Landskrona has continued during the whole year. The Division has been engaged in the general problem tacklings, experiment planning, performance evaluation, data handling and identification work.

The identification work on a generator resulted in the previously mentioned conference paper by Lindahl - Ljung (paper 1973).

As an example of a non-conventional application the identification techniques have been used to determine the thermal diffusivity in copper in a much more accurate way than before, see Leden et.al (paper 1973).

Measurement data from tankers have been received from Kockums Mekaniska Verkstad, Malmö. Some of the identification results are presented in Åström - Källström (paper 1973a).

The project on interior climate control has continued. Dynamic models have been identified for experiment rooms, total power consumption in buildings as well as hotwater supply to a block of buildings. A series of reports by L. Jensen describe the progress of this project.

The work on mixer settler dynamics reported last year /7/ has resulted in a published paper Aly - Wittenmark (paper 1973).

There is an increasing interest in application of identification methods to non-technical systems. One area is modelling of macro economic systems. One MS-thesis has been made and some joint studies have been initiated together with the Queen Mary College, London and the Economics Department at Lund University.

The work on biological systems has continued and several contacts have been established with clinical departments during the year. One MS-thesis where identification was used has been completed.

# 3. ADAPTIVE CONTROL

During the last year the research on adaptive control has been concentrated on

- o self-tuning regulators
- o convergence analysis for adaptive controllers

The aim of the self-tuning regulators is to tune the parameters of the regulator when the controlled system has constant but unknown parameters. The investigated regulators have very attractive asymptotic properties. These properties are however, heavily depending on the assumption of convergence. Special effort has therefore been taken in order to analyze convergence properties for adaptive controllers.

## 3.1 Self-tuning regulators.

The research on the self-tuning regulators has been performed along three lines

- o theoretical analysis
- o computer simulations
- o industrial applications

The work on the self-tuning regulators has resulted in one PhD-thesis. The thesis is summarized in Wittenmark (report 7312). The basic self-tuning algorithm that has been analyzed can be divided into two steps. Firstly the parameters in a model of the process are estimated using the method of least squares. Secondly the minimum variance regulator is computed based on the estimated parameters. These steps are repeated in each sampling interval. The necessary computations in each step are very few, which makes the algorithm suitable for real-time applications. The storage requirement for the algorithm is about 400 words. It is interesting to compare the complexity of a PI-regulator and the self-tuning regulator. There are about 4 operations (additions and multiplications) in a digital PI-regulator. The self-tuning regulator with two parameters requires about 34 operations. The number of operations for the self-tuning regulator is increasing with the square of the number of controller parameters. Thus the information processing is a magnitude larger in a self-tuning regulator compared with conventional regulators. A better performance can, however, compensate for the more complex computations.

The main property of the algorithm is that if the estimation converges then certain covariances of the output and cross-covariances of the output and input are equal to zero. If the controller contains enough number of parameters then the algorithm will converge either to a generalized deadbeat regulator if the changes in the reference signal are dominating or to a minimum variance regulator if the noise is dominating. The basic idea behind the self-tuning regulator is presented in Åström - Wittenmark (paper 1973b).

The basic algorithm has now been further analyzed. The obtained results are partly obtained through analysis and partly through extensive simulations using an interactive computer program. The simulations have thus been used to gain insight into the properties of the algorithm and to generate hypotheses, some of which were later proved mathematically. The results are presented in Wittenmark (report 7311)

The asymptotic properties of the basic algorithm are true under the assumption that the parameter estimates really converge. The convergence problem is however, very difficult to handle. In some special cases it can be shown that the algorithm converges. Using counter examples it has also been possible to show that the algorithm does not always converge. Extensive simulations and applications show, however, that the algorithm from a practical point of view has very attractive properties. The problems of convergence are further discussed below.

Some parameters must be specified when using the self-tuning regulator. These are the number of time-delays in the system, the number of parameters in the regulator, the initial values of the estimates and their covariances. It has been investigated, how the choice of these parameters influences the behavior of the algorithm. Experience has shown that in practice it is fairly easy to make the proper choice. These parameters are also much easier to choose than to determine directly the coefficients of a complex regulator. For the basic algorithm it has also been shown how reference signals and feedforward compensation can be included in the controller.

When the controlled system is non-minimum phase there are difficulties to use the basic algorithm. By increasing the number of time-delays in the model it is possible to get a suboptimal control of the non-minimum phase system. There are, however, other algorithms which automatically can handle non-minimum phase systems. An algorithm that can handle non-minimum phase systems as well as multivariable systems is presented in Peterka - Åström (paper 1973). The complexity of this algorithm is an order of magnitude larger than for the basic algorithm.

The basic self-tuning algorithm for single-input-single-output systems has been used to control a couple of industrial processes, Borisson - Wittenmark (report 7310).

A feasibility study of the control of an ore crusher has been done together with LKAB in Kiruna as described in Borisson - Syding (report 7318). Details concerning these applications are given in chapter 7.

Even if much insight into the nature of the self-tuning regulators has been gained during the last two years there still remain many problems to solve. Examples are the analysis of algorithms which can handle non-minimum phase systems, multivariable regulators, systems with time varying parameters as well as convergence properties of the algorithms.

## 3.2 Convergence analysis for adaptive systems.

A typical feature of the self-tuning regulator is that the outcome $\Theta_n$ of the identification depends on the feedback law. This in turn depends on the estimate. The sequence of parameter estimates can therefore be described by a non-linear, time-varying stochastic equation

$$\Theta_{n+1} = \Theta_n + \gamma_n f_n(\Theta_n, \ldots\ldots, \Theta_0; e_n) \qquad (3.1)$$

where $e_n$ is a sequence of dependent random variables. It has been shown that the ordinary differential equation

$$\frac{d}{dt}\Theta = g(\Theta) \quad ; \; g(\Theta) = E(f_n(\Theta, \ldots\ldots, \Theta; e_n) | \Theta) \qquad (3.2)$$

is a valuable tool for the analysis of (3.1). Asymptotic stability of (3.2) implies convergence for (3.1) and the trajectories of (3.2) approximate those of (3.1). Naturally, (3.2) is easier to analyse than (3.1). In this way convergence of the self-tuning regulator has been established for certain classes of systems. Also, the counter examples mentioned above, where the self-tuning regulator does not converge, have been constructed by careful analysis of (3.2).

The idea to associate an ordinary differential equation to adaptive schemes is outlined in Ljung (report 7218). The results of the application to the self-tuning regulator are reported in Wittenmark (report 7311). Theoretical analysis and application to general stochastic approximation algorithms will be given in forthcoming reports.

# 4. COMPUTATIONAL CONTROL

## The Program Library

A new operating system for the computer UNIVAC 1108 has made it necessary to modify some of the subroutines in the program library.

In connection with the development of the new program package for parameter estimation in linear state space models, some of the old subroutines have been improved and a few new subroutines have been added to the program library. The algorithms to transform continuous time linear systems to discrete time linear systems are presented in Källström (report 7309).

A new subroutine to iterate the discrete Kalman-Bucy filtering equations has been developed. The parameter estimation program depends heavily on a good minimizing method, so a new algorithm, Fletcher's switch method, has been tested and the algorithm seems to work very well.

## Methods for Optimization of a Function under equality Constraints.

This is a continuation of the work done by Mårtensson (report 7206). The methods used are based on Lagrange multiplier theory. They convert the constrained problem into an unconstrained one without introducing the ill-conditioning which is typical of the classical penalty function methods. Two types of methods are used, one where only one unconstrained minimization is needed and one where a sequence of unconstrained problems are solved. A theoretical study has made it possible to prove theorems, which give better understanding of the properties and usefulness of the methods. It has also made it possible to improve one of the algorithms. The new methods have been tested on a number of numerical problems and have been compared with the penalty function method. Considerable improvement over the penalty function method has been obtained even when the penalty function method uses extrapolation techniques to accelerate convergence. The work is presented in Glad (report 7323).

Optimal Control of a Sulfite Digester

A project concerning optimal control of the acid sulfite cooking process has been completed in collaboration with the Department of Chemical Reaction Engineering, Chalmers University of Technology.

The sulfite cooking process is controlled by the temperature and the pressure in the digester. The goal of the control was formulated to be to maximize the hemicellulose yield. At the same time the lignin content has to be decreased to a certain value. The temperature and pressure as well as temperature and pressure change rates may vary only within certain ranges. Temperature and pressure at the beginning and at the end of the cook are given.

This leads to a mathematical optimization problem with five state variables, which are modelled by complex non-linear differential equations. The problem includes terminal constraints as well as constraints on input and state variables. Furthermore the problem is singular (i.e. the second derivative of the Hamiltonian is singular).

The formulated problem was solved numerically using a method based on Differential Dynamic Programming. The method and the solution are discussed in Mårtensson-Ljung-Nilsson (report 7320). The optimal control strategy does not differ in any fundamental way from the type of control used in industry. However, the project has demonstrated the possibility to solve realistic and very complex optimization problems numerically.

Numerical Methods for Optimal Control

Numerical methods have been developed for optimal impulse control problems. This work was done during Mårtensson's visit at University of Southern California, Los Angeles, USA, and is documented in two USC-reports ("Numerical Methods for Optimal Impulse Control, I-Linear Systems with a Quadratic Cost" and "Numerical Methods for Optimal Impulse Control, II-Nonlinear Systems").

The "Constraining Hyperplane Technique" for state variable constrained problems (Mårtensson, report 7206) has been presented at the 1973 Joint Automatic Control Conference, Columbus, USA. Present work is concerned with convergence properties of the method.

Parametric invariance of dynamic systems has been studied by Mårtensson in the USC-report "Least Square Identifiability of Dynamic Systems". These results also provide some further insight into the relations between local uniqueness of the optimal parameters and controllability of the linearized system.

## 5. REAL TIME COMPUTING

This project is performed in close contact with the PDP 15 computer, which can be connected to equipment in the laboratory or to processes outside the building. This computer is and has been a useful tool in learning and teaching real-time computerized control as well as computational methods in control theory.

### Real Time Computing Laboratory.

The principal part of this facility is of course the PDP 15 computer itself but it contains also a number of processes that can be connected to the computer's analog interface. These laboratory processes have been described in earlier reports. There has been two improvements during the year.

1. The primary (core) memory of the PDP 15 has been doubled to 32k. This has greatly enhanced the possibilities both in real-time applications and in implementing interactive programs.

2. A new process has been built. It is a system of three tanks where water is circulated. The water flow can be controlled by two pneumatically actuated valves, one before the first tank and after the pump, the other after the third tank. Transducers for the measurement of the flow through the valves as well as for the three tank levels are provided. Actuators and transducers are of pedagogical reasons of industrial type. The process contains two analog regulators and an interface to the PDP 15. Thus it can be run in a stand-alone mode as well as connected to the digital computer. Variables to be controlled can be chosen either as water flow or as water level in one or more of the tanks.

## Real - Time Control & Programming

Several projects have been running in parallel. In some cases the emphasis has been on testing advanced control algorithms, in other the purpose has been to gain experience in using commonly used DDC-algorithms.

1. In a master thesis by Jan Thulin (MS-thesis RE-131) the implementation of digital PID-algorithms on "BOMMEN" was studied. BOMMEN is a process in the laboratory where a ball is balanced on a moving (horizontal) bar. The study included the choice of sampling interval, the method of implementing the derivative action, the use of conditional integration etc.

2. A self-tuning regulator as described elsewhere in this report was tested in cooperation with LKAB, Kiruna, Sweden. The control programs were run on the PDP 15 computer in Lund while the controlled system was an ore crushing plant in Kiruna. Measurements and control actions were transmitted on the public telephone lines. The most spectacular thing was the distance between Lund and Kiruna 1800 km, thus it was the longest DDC-loop known, see Borisson - Syding (report 7318).

3. Last year a remote data aquisition terminal (a HP Coupler - Controller with digital voltmeter) was interfaced to the PDP 15. It has during the year been used for room temperature control experiments in cooperation with the Department of Building Sciences, see Jensen (report 1973a).

4. Dead-Beat II control of a laboratory process, the heatrod, has been performed, using the PDP 15 computer. Different finite - dimensional models for the process have been compared and the result is summarized in Holst (report 7206(C)).

5. The extra 16k core memory on the PDP 15 meant that it would be feasible to run an expanded version of the real time monitor RSX (Real - Time Systems Executive). The new monitor RSX - Plus was implemented during the year. It took some doing though, because it assumed a somewhat different hardware configuration than was available on our PDP 15. After some modifications it runs nicely. The main advantage is that it supports the utility programs that are needed for program development such as editor, fortran compiler etc, in parallell with normal real-time tasks such as data-aquisition and control programs. This is a great and valuable improvement over the old version.

6. In conjunction with the new laboratory process described above, a simple DDC-package was designed. It can perform several of the functions commonly found in industrial DDC-packages. A distinguishing feature is that the loop-records are stored in two-way lists. This makes it extremely easy to introduce or remove loops on-line. This package has also been used in laborations on the under-graduate level.

Interactive Programs

The interactive programs such as SYNPAC, which was described in last year's report, has been in frequent use. They have also experienced flattering international interest. SYNPAC has been presented at two international conferences Wieslander (1972) and Wieslander (1973). The work in this field has proceeded on different levels:

1. The institute has got one version of the simulation program CSMP from SAAB in Linköping. This program makes it possible to simulate linear systems on the computer. It is also possible to use some simple non-linearities such as relay, deadzone, hysterisis etc. The program has been modified in order to make it easier to use. The program is now command oriented and new plotting facilities are included. The revised version of the CSMP package is presented in Mattsson (MS-thesis RE-127).

2. A master thesis by B. Kennedy (MS-thesis RE-128) resulted in an interactive program for synthesis of closed loop single input - single output linear dynamic control systems on continuous time transfer function form using the root locus method. The locus is computed by solving the characteristic equation for different values of the gain parameter (K). The step-length in K is varied automatically to provide nearly equal spacing between the locus points on the display. As a check the closed loop system step input response can be calculated and displayed.

3. From the Department for Computing and Control, Imperial College, London we have received a program similar to the one above called LOCUS. It is also an interactive program intended to solve approximately the same design problem. The method to compute the root-locus however, is quite different in that a curve-following technique has been employed. This makes it feasible to solve a somewhat more general problem as time-delays in the system is easily included. On the other hand there will be a conflict between the step length in the curve following algorithm and the shortest distance between poles and/or zeroes in the system and controller transfer functions. This condition that is not uncommon in

practise, does not affect the previous method, Wieslander (report 7204(C).

4. The above program, LOCUS, is a part of a much greater package, "The Classical Design Suite", at Imperial College. As a step in a continuing exchange of experience and ideas we have received a copy of that package which is now being implemented. The package includes e.g. modules for Bode, Nichols and Nyquist plots.

The work above has taught us an important lesson. I.e. that the difficult and time-consuming part in moving design programs from one installation to another is the modification that must be done to the plotting (display) subroutines. Differences in the display hardware can require extensive modifications. A standardization in this field is urgently needed. Also, the programs in §§ 2,3 and 4 above are of the question and answer type in contrast to the command-driven programs that are usually preferred at our institute. The experience has strengthened our opinion in this respect.

Preliminary work on a data analysis package has been done during the year. A working and documented version will probably be available later this year. The package can be described as follows:

IDPAC is an interactive command driven program for time series analysis and system identification. It accepts experimental data from magnetic - or paper - tape and provides the user with effective means for plotting and data modification such as e.g. trend correction and filtering. Spectral analysis may be performed as well as least squares and Maximum Likelihood estimation of multiple input - single output systems. The accuracy of the models may be tested and simulations carried out with or without noise.

Frequently used command sequencies may be linked into macros i.e. subroutines consisting of commands with formal arguments. Thus an arbitrarily long command sequence may be initiated using a single command.

## 6. SYSTEM THEORY

The research activities within the framework of the graduate program also include system theory. The most important contributions are summarized below.

### Linear Systems Theory

Kalman filters usually need an à priori statistics for the initial state. The case when part of the initial state is unknown, has been investigated using different approaches. The problem of minimal variance, linear unbiased estimates is the dual of a linear quadratic control problem with constrained endpoint. Two preliminary reports have appeared during the year, Hagander (report 7219) and Hagander (report 7303), while a final report is under preparation.

### Distributed parameter systems

Professor Ruth Curtain, University of Warwick, England, lead a qraduate course on distributed parameter systems. A survey introduction to the filtering problem in distributed parameter systems is given in Curtain (report 7301).

Multivariable Systems

The inverse system concept plays a crucial role in several important control problems, which treat various aspects of the servo problem. A given system may, however, have several inverses with different properties. It is therefore important to understand clearly the difference between various inverses, particularly their stability properties. In Bengtsson (report 7305) inverses of minimal dynamical order are considered. It is shown how such inverses can be obtained by a sequence of basic operations on the original system. Minimal system inverses have one particularly interesting property: its characteristic polynomial divides the charactaristic polynomial for an arbitrary inverse. The minimal inverse is thus stable provided there is any stable inverse. This property is of importance in the servo problem.

Work has also been carried out in another important control problem, the regulator problem. In many actual systems there is a desire to restrict the complexity of the feedback structure, e.g. due to constraints in measured signals or information exchange. This means that only output or restricted output feedback is permitted, where each output variable is allowed to be connected to a subset of the inputs. This kind of problems are treated in Bengtsson - Lindahl (report 7225).

In this report, the restricted feedback problem is attacked in two steps: (a) a state feedback regulator is designed under the hypothesis of a completely free feedback structure, (b) the state feedback regulator is fitted into a regulator with a constrained feedback structure using successive weightings on a dominant eigenspace. This approach leads to a design scheme suitable for implementation in an interactive mode. The design scheme has been successfully applied to find a simple regulator for a power system, see Bengtsson - Lindahl (report 7225).

Pseudoinverses

An iterative method (earlier proposed in the literature) for computing pseudoinverses, has been analysed in cooperation with professor G.W. Stewart. The result of the analysis will be published in Söderström - Stewart (paper 1973).

It is shown in the paper that the method is not self-correcting.For this reason the iterations must be stopped in correct time. It is shown how to decide when it is appropriate to stop the iterations. Another analysis shows that the method does not give larger errors in the final result than other methods for computing pseudoinverses. However, the method is very time consuming, which is a strong drawback.

## 7. APPLICATIONS

A number of applications from different fields are given in this section. In the applications model building techniques as well as control strategies, described in the previous sections have been used.

Power Systems (S. Lindahl)

The application of linear quadratic control theory to the control of power systems has been treated earlier. One serious drawback of the solution to this problem is that it requires complete information exchange between the power stations. In the report Bengtsson - Lindahl (report 7225) the problem of reducing feedback laws has been treated. Analysis of a power system with three generators indicates that the proposed method is feasible. The reduced feedback law does not require any information exchange.

In connection with real-time control of power systems much interest has been devoted to the power system state estimation problem. To apply modern filtering theory to this problem it is often assumed that the power system can be described by the model.

$$x(t+1) = x(t) + v(t)$$

where x is the state vector, and v is a white noise process. In Neiderud (MS-thesis RE-126) the validity of this assumption has been investigated using simulated data from a small power system model. The data are generated using a dynamic model of the generators, exciters and govenors. A state estimator based on the model was found to work well, provided we can find a suitable value of the covariance matrix of the noise v.

The economic load dispatch problem has been investigated by Ragnarsson (MS-thesis RE-129). A new method using the concept of "multiplier function" described in /7/ has been developed and tested. A first order method for the adjustments of the multipliers has been utilized. The initial rate of convergence is high but is reduced in the neigbourhood of the solution. The accuracy is compatible with other methods.

On February 5 Sydsvenska Kraft AB informed us that they were planning dynamic test on a 70 MW gas-turbine situated in Halmstad. On March 9 our participation was planned on a meeting at Sydsvenska Kraft AB and on March 23 we took part in a step response test. We were also allowed to introduce a PRBS-sequence disturbance on the fuel flow. The collected data are currently analyzed.

Thermal power plants (K. Eklund, I. Gustavsson, S. Lindahl).

The data obtained from the experiments in 1969 at the thermal power station, Öresundsverket in Malmö, have been used for identification of non-linear boiler models. Primarily it was a feasibility study of non-linear identification in order to find out the applicability of available methods.

The simple non-linear model developed earlier at the Division gave the main structure of the model. Due to the special structure of the model it was possible to estimate some of the parameters by linear regression form static relations. The rest of the parameters in the model were estimated using an identification program developed at the Division, see chapter 2.2.

The obtained model predicted active power and drum pressure quite well even for different load levels and may be of sufficient accuracy, e.g. for control purposes. However, the remaining disagreement between the model output and the measured output suggests that there are phenomena in the process which can be observed in the data but which are not included in the model. One possible explanation is the changing feedwater temperature. The study shows that non-linear identification still requires a lot of computing time which restricts the applicability in practice. The result was presented in an invited case study at the 3rd IFAC Symposium on Identification and System Parameter Estimation in the Hague, 1973, Eklund - Gustavsson (paper 1973). The results were presented together with a selection of the results of the drum boiler identification using single input single output difference equation models and multivariable linear state space models published in previous reports and papers.

The studies of non-linear models for the drum boiler are now continued as an MS-thesis, in which another non-linear model structure is used.

Nuclear Power Reactor (G. Olsson).

The collaboration with the OECD Halden Reactor Project, as reported in the last annual report has continued. No new experiments have been performed during the last year, but a lot of analysis and identification work has been done, especially for multivariable experiments. Different approaches have been tried out to find a suitable linear multivariable representation of the plant.

An experiment with varying operating conditions has also been analyzed. The reactor was represented by linear differential equations with time varying parameters. Those parameters were tracked with an Extended Kalman filter. A summary of the work is presented in Olsson (paper 1973)

Paper Machine Models (B. Häggman, I. Gustavsson, K.J. Åström)

Our efforts in the area of paper machine control have been continued. Mathematical models of headboxes have been analyzed in Swärd - Rasmusson (MS-thesis RE-121). The study includes open headboxes, closed headboxes, headboxes with Hornbostel holes and headboxes with internal overflow.

We have also been participating in a project at the STFI (Svenska Träforskningsinstitutet), Stockholm. A first part of the project has been to develop models for different parts of a paper machine. Models have been developed both from theoretical analysis of the physical process and from identification using measurements from a pilot plant at the STFI as well as from a big newsprint machine. We have participated in the developement of the physical models and in the planning of the identification experiments. Furthermore the evaluation of the data has been performed using our identification programs, mainly the interactive identification program package on the PDP 15. The work has been mainly carried out by Mr B. Häggman, STFI and is reported in the licentiat thesis, Häggman ( 1973 e-i).

Based on our current understanding a simple paper machine model has also been developed, Åström (report 7305(C)). The model explains the gross features of paper machine dynamics. It can be used for estimates and teaching purposes. It is also a nucleus for a catalogue of process models.

Adaptive rules for changing the reference values as a response to varying noise levels have been studied in Borisson and Brissman (MS-thesis RE-115).

A simple model of a paper machine has been simulated on an analog computer. The model contains five state variables, seven input and seven output signals. Through the simulations it was verified that the gross features of the model seem to be correct. Further the effect of head-box control was investigated. The work is reported in Pettersson (MS-thesis RE-123).

Adaptive control of a paper machine (U. Borisson and B. Wittenmark).

A joint study with Billerud AB has been carried out at the Gruvön Mill in Grums. A self-tuning regulator has been used in moisture content control on PM6, a paper machine producing fluting. The algorithm was implemented on an IBM 1800 computer, which is used for process control in the mill.

The steam pressure of the last drying section of the paper machine was used as control signal. A feedforward loop from the couch vacuum was included in the regulator. Experiments of different lengths were done. The algorithm was easy to start up and the parameter choice was not crucial. The self-tuning regulator managed to follow the reference value of the moisture content better than the original regulator. The parameters resulting from the self-tuning algorithm were then inserted in the DDC-package.

The systems engineer at the Gruvön mill could easily take over the operation of the self-tuning program. He is now using it to design a combined moisture content and basis weight control loop on PM4, a kraft paper machine.

The project at the Gruvön mill is described by Borisson - Wittenmark (report 7310). A version of this report has been accepted for publication at the 4th IFAC/IFIP Conference on Digital Computer Applications to Process Control in Zürich, March 1974.

Adaptive control of an ore crusher (U. Borisson).

The joint project with LKAB, Kiruna, devoted to control of an ore crusher at the crushing plant in Kiruna, Kiruna Finkrossverk, has been completed. The purpose has been to study the feasibility of controlling an ore crusher with a self-tuning regulator and to provide experience on the use of real industrial processes for remote control experiments.

The control aims at keeping the production on a certain level, as high as possible, without overloading the crusher. The process has some characteristic features due to considerable transport times and special dynamics. Sometimes the ore may be accumulated on a transport band in a closed loop, and then the crusher power becomes more difficult to control.

The PDP computer at the Division of Automatic Control in Lund was connected to the crushing-plant in Kiruna via a public telephone line and low speed modems. The data signals were transmitted about 1800 km. A special process interface was built, and it was connected to the crusher in Kiruna. All practical arrangements are described in Andersson - Borisson - Braun - Syding, (report 7318(C)).

The results from the study showed that a self-tuning regulator with good control properties could be designed for the crusher, Fig 7.1. The regulator made it possible to operate on high power levels. The project, including the control experiments, is described by Borisson - Syding, (report 7318). The experiences from the use of tele-processing for remote control were good.

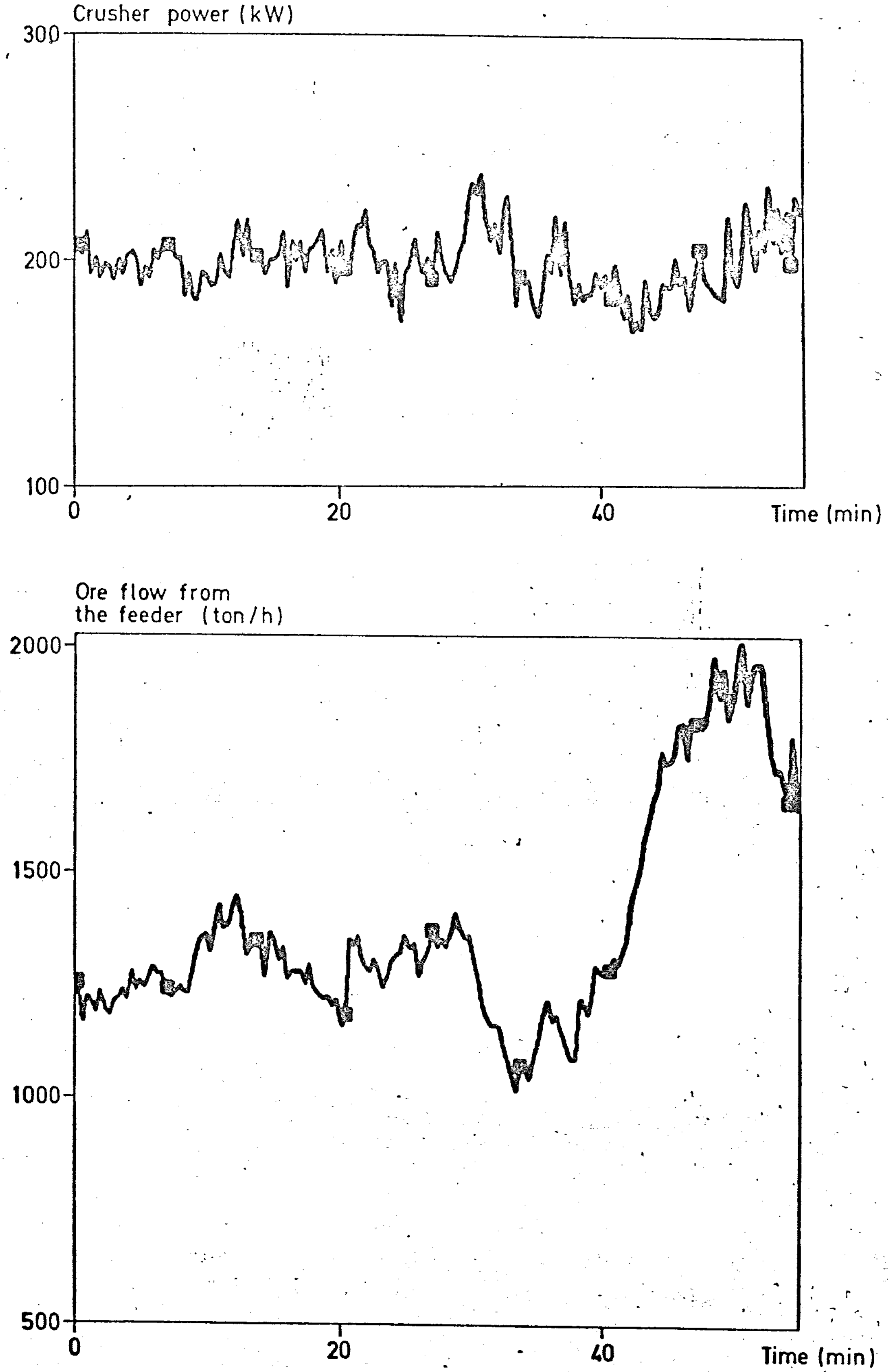



Figure 7.1 - Registration from an on-line experiment where the ore crusher in Kiruna is controlled from a computer in Lund with a self-tuning regulator. At the end of the registration the ore is getting easier to crush, and it is seen how the regulator increases the ore flow, to keep the crusher power on a high level.

Ship Dynamics (K.J. Åström, C. Källström)

Measurements from tankers have been received from Kockums Mekaniska Verkstad, Malmö, and one data set from ~~two~~ 255 000 ton ship has been analysed. Parameters of a third order linear, continuous state model, where the rudder angle is the input and the sway velocity, the yaw rate and the heading are the outputs, are estimated and the results are presented in Åström - Källström (paper 1973a). In this paper the ideas behind the new program package for parameter estimation in linear state space models are also given. Discussions with the Swedish State Shipbuilding Experimental Tank (SSPA), Göteborg, and Kockums Mekaniska Verkstad, Malmö have shown that some of the problems, which have arisen are due to the fact, that non-linear terms have not been taken into account in the model.

Wastewater treatment plants (G. Olsson)

Early in 1973 a feasibility study was initiated concerning control problems in wastewater treatment plants. The study has been supported by the Swedish Board for Technical Development (STU) and the Division has collaborated with the Axel Johnson Institute for Industrial Research, Nynäshamn, the National Environment Protection Board, Solna, the Käppala Wastewater Treatment Plant, Lidingö and the Divison of Hydraulics, Lund Institute of Technology. G. Olsson has been mainly responsible for the study. It has been undertaken by literature studies, experiments at a pilot plant in Malmö, visits at several plants and institutions. A travel in the USA and in Canada has also been made and is reported in Olsson - Ulmgren (report 7323(C)). The results of the study will be presented soon in a forthcoming report. Experimental data have been given from Systems Control Inc., Palo Alto, California for a biological wastewater treatment plant. Identification experiments on chemical precipitation have also been performed at the pilot plant at the Sjölunda wastewater treatment plant in Malmö. The analysis and identification results will soon be presented in an MS-thesis by P.O. Gutman and R. Olsson.

Fertilizer plant (G. Olsson)

In the summer 1972 a study in cooperation with Supra, Landskrona, was initiated. The aim of the study was to get dynamical models of a granulator process with recirculating material flow in a NPK fertilizer plant. With such a model it could be possible to better understand stability problems and how to overcome these problems by better control.

Two experiment series have been performed during the year, one with only natural disturbances and one with external disturbances applied at the output material flow. Severe instrumentation and measurement difficulties have made the experiments and identifications cumbersome, but some realistic models have been achieved. It has also been possible to show more precisely where better instrumentation is needed.

For the next phase it has to be decided if more instrumentation should be installed in the plant. The results are hitherto presented in two MS-theses, Gabrielsson - Luterkort (MS-thesis RE-119) and Cronstedt - Salmberg (MS-thesis RE-125).

Heat diffusion process (B. Leden)

Different methods for determining parametric models of a one dimensional heat diffusion process have been investigated. The methods are a periodic termperature method, an on-line Least Squares method and a Maximum Likelihood method. Process inputs are the end temperatures of a long copper rod. Process outputs are the temperatures in seven equidistant points on the rod. The process is one of the experimental processes in the laboratory.

The periodic temperature method has gained widespread acceptance as an accurate method for determining the thermal diffusivity. The process is excited by a sinusoidal signal of a frequency high enough to guarantee that the rod becomes semi-infinite. The thermal diffusivity is obtained from measurements of the amplitude and phase relationships along the rod.

The on-line Least Squares method approximates the distributed parameter system using finite differences and an error function is obtained. By minimizing the sum of the error squared over an observation interval the required parameters are determined. This method is extremely fast and is applicable to an arbitrary distributed parameter system.

The Maximum Likelihood method transforms the model of the diffusion process into a finite dimensional system of ordinary differential equation by approximating the partial derivative in the z-direction using finite difference for-
mulae. The order of the model used for identification was 21. By maximizing the likelihood function the unknown parameters are estimated. This method can be efficiently used to check the validity of the heat equation model. Further errors in the characteristics of the temperature transducers can be estimated and the influences of these errors on the thermal diffusivity diminished.

The periodic temperature method and the on-line Least Squares method require much less storage and computation time than the Maximum Likelihood method. However, these methods are less accurate than the Maximum Likelihood method. The periodic temperature method and the Maximum Likelihood method are insensitive to high noise levels as distinguished by the on-line Least Squares method. Errors in determining the thermal diffusivity are of the order of 0.3%, 1% and 0.1% for the periodic temperature method, the on-line Least Squares method and the Maximum Likelihood method, respectively.

The results clearly show that system identification techniques can be powerful tools for obtaining precise measurements of physical variables. The results are published in Leden et.al. (paper 1973). This study was performed in collaboration with Dr M.H. Hamza, the University of Calgary, Canada.

## Control systems in climatized buildings † (L. Jensen)

During the year the following three items have been completed under the project.

- o interfacing of a coupler/controller system
- o experiments with computer control of roomair temperature
- o modelling and forecasting of heating of buildings

### Interfacing of a coupler/controller system

A coupler/controller is a kind of process interface to a process computer (in this case a PDP 15). It is connected as a teletype by two wires or over the telephone net. This property makes it possible to control processes far away from the computer. The equipment has 10 analog inputs and

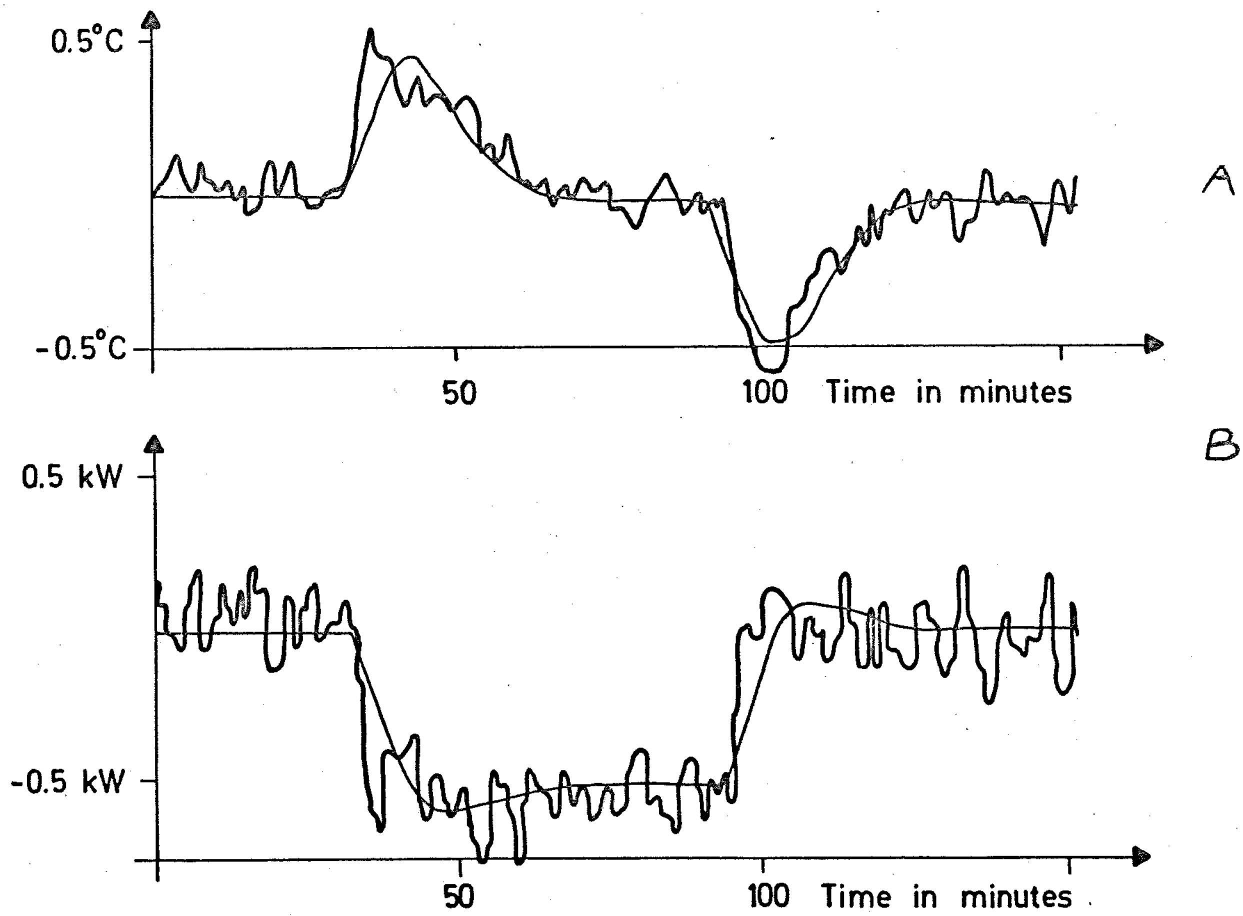
† Project D 698 from the National Swedish Board of Building Research.

4 logical outputs. The output part of the system and ten termistor bridges for temperature measurements were constructed and built. Programs that are necessary to communicate with the c/c system have been written and tested. The work with the c/c system is documented in Jensen (report 1973a).

Experiments with computer control of room air temperature

The experiments concern control of the air temperature of a fullscale test room at the Division of Building Science, Lund Institue of Technology. The room is heated by two electrical radiators. Several types of control laws to keep constant room air temperature under varying conditions have been tested. The control laws were implemented on the PDP 15 computer, which was connected to the c/c system at the test room via wire. The results are discussed in Jensen - Ljung (report 7322). The experiments clearly show that control laws based on dynamic models of the system have better performance than conventional ones.

Models, obtained from previously reported identification experiments were used (see Jensen (report 1973b)). These models were found to be very suitable to synthesize control laws. The predicted (simulated) behaviour of the closed loop system differed only little from the experimental results. See figure 7.2.




<u>Figure 7.2</u> - Comparison between simulation and experimental results when using a fourth order regulator based on the identification results. A: Thin line: Simulated temperature. Thick line: Experimental result. B: Thin line: Simulated input signal. Thick line: Experimental result.

Modelling and forecasting of heating of buildings.

The total power consumption in two buildings (in Tensta and in Bollnäs) has been measured for a period of about two years. This has been part of the project "Power supply of buildings" supported by the National Swedish Board of Building Research.

Different models have been adjusted to these data. The heating power was found to depend basically only on the indoor-outdoor temperature difference. The result was not improved significantly by using sun radiation and wind as second and third input. The results are documented in Jensen (report 1973c). Dynamic models were also tested but with unsatisfactory result.

Also, a model for the hotwater supply of a block of buildings has been used for forecasting. The model contains a periodic deterministic part and a term proportional to the outdoor temperature. The results are discussed in Jensen (report 1973d).

Economic Control Problems (K.J. Åström)

There is an increased use of stochastic control theory in economic literature. Identification and parameter estimation problems have also been prominent in econometrics for a long time. The development of the methods have largely been parallell in the fields of Automatic Control and Economy. There are, however, important differences. Data is usually much more accurate and much more accessible in the engineering applications. To get some insight into the similarities and differences, we have applied our identification techniques to macroeconomic modelling. This is reported by Johansson - Martinsson (MS-thesis RE-116).

The group from Queen Mary College, London, which is concerned with modelling the British economy also visited us to apply our interactive programs to their data. Using reasonable initial estimates it took about a week for them to obtain a complete model.

To educate ourselves we have also run a course "Control Theory and Economic Policy" jointly with professor Thâlberg at the Economics Department at Lund University.

Biological Control (P. Hagander)

During the year the work on biosystems was supported by the Swedish Natural Science Research Council, and the grant is now renewed for a second year.

The work on genetic population models is summarized in Hagander - Johansson (report 7315). A population is divided into different groups depending on their possibilities to interbreed. The dynamic behavior of these groups is simulated generation after generation. The incompatibility system discussed is one of the simpliest used in genetics. Still the mathematical model describing the assumptions is highly non-linear, and its behavior was almost unknown. The only intuition was generalizations from the degenerate case with only three groups, which however, is shown to have drastically different behavior. A few individuals of a new group influences a system with many groups only in the very long run, while it causes large oscillations in a highly interbreeded system with only a few groups left.

Two master theses were completed during the year. The balancing capability of humans has been tested using online measurements and analysis on the PDP 15 computer, see Kjellander - Selander (MS-thesis RE-117). The spectrum of the variation of the body masscenter is obtained immediately after an experiment. Parametric models are also obtained using regression and maximum likelihood analysis. The effect of certain deseases and treatment like alcohol and hard work is investigated. The changes in mean square deviation is larger than the frequency changes. Until further physiological structure and perhaps external perturbations are used, it is difficult to use the procedure for diagnostic purposes. The work is a continuation of the collaboration between Ivar Gustavsson and Dr Haldo Östlund, Neurological Clinic, Lund University Hospital.

The dosage of digitalis was considered in Svensson (MS-thesis RE-114) and control schemes were obtained using stochastic control. Although the dynamics are assumed to be known, a second order model from University of Southern California, there remain several problems. The input can for instance only assume certain values, the number of pills to be taken. Another limitation is that the responding plasma concentration for a certain constant input may vary considerably between the patients and from time to time. A major purpose must be to estimate this relation. The correlation between plasma concentration and effect is well accepted but difficult to quantify.

At contacts with Doc B. Nosslin, Malmö, simple impulse response identifications were made on tracer data. Although the data does not contain enough information for a correct system description, wanted parameters can be obtained with good accuracy.

Similar facts lie behind the work together with Clinical Physiology, Lund, on renal clearence measurements. Two different methods are currently in clinical use. One method uses the impulse response and assumes that the final part of the response can be represented by a simple exponential decay. A correction factor, obtained from a large statistical material, gives a fairly good estimate of the clearence constant from bloodsamples taken only during the fourth hour. The other method uses continuous infusion. Blood and urine measurements are done when the plasmaconcentration is fairly constant usually during the second hour. The feasibility of a new method using only blood samples and an external radioactive measurement is under investigation. The indicator infusion is controlled to get steady state conditions as soon as possible.

## 8. TECHNOLOGICAL ASSESSMENT

The applicability of some of the results has already been proved. Here it is intended to indicate the status of some theoretical results in order to make it easier for users of the theory to see fields of new applications.

### System Identification

System identification has been shown to be a powerful tool for model building, both for technical and non-technical applications. Identification of linear multi-input-single-output can now be made by routine. Identification of multivariable systems is far more difficult, but some experiences have already been gained. A wide field of applications opens up here.

Control strategies based on identification models have been implemented in real applications. Typically low order models are most often sufficient for those purposes.

It is worthwhile mentioning that the identification programs can be used even by people with little special experience in the identification methods. As an interesting example the programs have been used by people from the Economics Department at Lund University and from Queen Mary College in London.

### Adaptive Systems

Self-tuning regulators will certainly be applied to a large number of different systems in the future. Self-tuning regulators have been implemented in two full scale processes, and demonstrated how advanced regulators can improve the process behaviour significantly compared to conventional controllers. It seems to be feasible to use similar ideas also for more complicated dynamical systems such as non-minimum phase and multivariable processes.

The Self-tuning regulators have a large potential use because they are relatively simple to implement in a process computer. The storage requirement and the computing time are quite modest.

Computational Control

In a research project the availability of a well documented computer program library is of the utmost importance. The use of optimal control for nonlinear systems can be made more available by standard program packages and well documented software. A good demonstration is the application of optimal control to the sulfite digester. This problem is still one of the most difficult problems that has been solved in the area of optimal control. Still it was possible to solve part of it within a MS-thesis during three months when the programs were available.

Interactive Computing

Interactive programs will certainly be even more important, not only for research but also for a wide spread use of modern control ideas to applications. Non-specialists can use those type of programs in a very short time to achieve meaningful results.

Remote Control

It has been demonstrated the technique to connect full scale industrial processes over the public telephone network to an existing process computer. Especially feasibility studies can be performed in this way with a minimum amount of investments.

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| Skrivhjälp | Gudrun Christensen |
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# APPENDIX B

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Söderström, T. and Stewart, G.W. (1973b) "On the numerical properties of an iterative method for computing the Moore-Penrose generalized inverse", SIAM journal on numerical analysis, 10, No 6.

Wieslander, J. (1972) "Computer aided design of linear feedback regulators using linear quadratic control theory", ONLINE 72, Conference Proceedings, Brunel University, Uxbridge, England, September 1972.

Wieslander, J. (1973) "Interactive programs for computer aided design", Proceedings from IEE Conference on "Computer aided control system design", University of Cambridge, Cambridge, England, April 1973.

TECHNICAL REPORTS

Report 7218 Ljung, L.: Convergence Concepts For Adaptive Structures, August 1972.

Report 7219 Hagander, P.: Linear Filtering With Unknown Initial Values, August 1972.

Report 7220 Åström, K.J.: Modelling and Identification of Power System Components, August 1972.

Report 7221 Åström, K.J.: Process Control 1971 - 1972. Final Report, project 71-50/U33, September 1972.

Report 7222 Roggenbauer, H., Seifritz, W. and Olsson, G.: Identification And Adjoint Problems Of Process Computer Control, September 1972.

Report 7223 Olsson, G.: Power-Nuclear Plants, September 1972.

Report 7224 Åström, K.J.: Properties Of The Equations Describing A Tank Reactor, September 1972.

Report 7225 Bengtsson, G. and Lindahl, S.: A Design For Incomplete State Or Output Feedback With Applications To Boiler And Power System Control, November 1972.

Report 7226 Keviczky, L.: On Some Questions Of Input Signal Synthesis, November 1972.

Report 7227 See Report 7203(C).

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| Report 7228 | Söderström, T.: On The Convergence Properties Of The Generalized Least Squares Identification Method, November 1972. |
| Report 7229 | Sternby, J.: On A Production Planning Problem, December 1972. |
| Report 7230 | Wittenmark, B.: Master Theses In Automatic Control 71/72 (Examensarbeten 71/72), December 1972. |
| Report 7301 | Curtain, R.: Filtering In Distributed Parameter Systems - A Survey Introduction, Janurày 1973. |
| Report 7302 | Aly, G. and Wittenmark, B.: Dynamic Behaviour Of Mixer-Settlers II. Mathematical Models And Identification Methods, January 1973. |
| Report 7303 | Hagander, P.: Initializing A Kalman Filter When Initial Values Are Known, February 1973. |
| Report 7304 | The Report was nerver published. |
| Report 7305 | Bengtsson, G.: Minimal System Inverses For Linear Multivariable Systems, March 1973. |
| Report 7306 | Söderström, T. and Åström, K.J.: Uniqueness Of The Maximum Likelihood Estimates Of The Parameters Of A Mixed Autoregressive Moving Average Process, March 1973. |
| Report 7307 | Söderström, T.: On The Uniqueness Of Maximum Likelihood Identification For Different Structures, March 1973. |

Report 7308 Söderström, T.: An On-Line Algorithm For Approximate Maximum Likelihood Identification Of Linear Dynamic Systems, March 1973.

Report 7309 Källström, C.: Computing Exp(A) and $\int$Exp(As)ds, March 1973.

Report 7310 Borisson, U. and Wittenmark, B.: An Industrial Application Of A Self-Tuning Regulator, April 1973.

Report 7311 Wittenmark, B.: A Self-Tuning Regulator, April 1973.

Report 7312 Wittenmark, B.: Self-Tuning Regulators, April 1973.

Report 7313 Gustavsson, I.: Survey Of Applications Of Identification In Chemical And Physical Processes, March 1973.

Report 7314 Söderström, T.: Uniqueness And On-Line Algorithms In Identification Of Linear Dynamic Systems, April 1973.

Report 7315 Hagander, P.and Johansson, L.: Incompatibility Alleles; Characteristics Of A 1-locus System, April 1973.

Report 7316 Olsson, G.: Modelling And Identification Of Nuclear Power Reactor Dynamics From Multivariable Experiments, April 1973.

Report 7317 Wittenmark, B. and Åström, K.J.: On Self-Tuning Regulators, May 1973.

Report 7318 Borisson, U. and Syding, R.: Control Of An Ore Crusher - A Feasibility Study Of Self-Tuning Control And Remote Processing, June 1973.

Report 7319 Bramsmark, G., Bäckström, P., Gutman, P-O., Jeppsson, H., Johansson, G., Kronqvist, P., Malmqvist, K., Nerman, H., Olsson, R., Perby, M-L., Ragnarsson, J.: PH-Reglering, June 1973.

Report 7320 Mårtensson, K., Ljung, L. and Nilsson, L-O.: Optimal Temperature And Pressure Control Of The Acid Sulfite Cooking Process, June 1973.

Report 7321 Bengtsson, G., Borisson, U., Glad, T. and Gustavsson, I., Hagander, P. and Ljung, L.: Analysis And Simulation Of A Macro Economic Model, July 1973.

Report 7322 Jensen, L., Ljung, L.: Experiments With Computer Control Of Room Air Temperature, July 1973.

Report 7323 Glad, T.: Lagrange Multiplier Methods For Minimization Under Equality Constraints, August 1973.

Report 1973a Jensen, L.: Ett coupler/controllersystem (A Coupler Controller System, in Swedish), Arbetsrapport 1973:6, Division of Automatic Control and Division of Building Sciences, Lund Institute of Technology.

Report 1973b Jensen, L.: Dynamiska modeller för ett rum - del 2 (Dynamical Models For A Room II, in Swedish), Arbetsrapport 1973:7.

Report 1973c Jensen, L.: Statiska modeller för uppvärmning (Static Models For Heating, in Swedish), Arbetsrapport 1973:10.

Report 1973d Jensen, L.: Veckoprognoser av fjärrvärmeeffekt (Weekly Prognoses Of District Heating Power, in Swedish), Arbetsrapport 1973:9.

Report 1973e Häggman, B.: Olinjära matematiska modeller för våtpartiet på en pappersmaskin (Nonlinear Models Of The wet End Of A Paper Machine).

Report 1973f Häggman, B. and Gustavsson, I.: Identifiering av dynamiken hos en experiment pappersmaskin. Del 1. Mätning vid säckpappersproduktion (Identification Of The Dynamics Of An Experimental Paper Machine. Part I. Measurements Of Such Paper Production).

Report 1973g Häggman, B.: Identifiering av dynamiken hos en experiment pappersmaskin. Del 2. Mätning vid journalpappersproduktion (Identification Of The Dynamics Of An Experimental Paper Machine. Part II. Measurements Of Journal Paper Production).

Report 1973h Häggman, B.: Identifiering av dynamiken hos en experiment pappersmaskin. Del 3. Mätning vid hög maskinhastighet (Identification Of The Dynamics Of An Experimental Paper Machine. Part III. Measurements At High Machine Speed).

Report 1973i Häggman, B.: Identifiering av dynamiken hos en stor tidningspappersmaskin (Identification Of The Dynamics Of A Large Newsprint Machine).

TECHNICAL REPORTS (internal)

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| Report 7201 C | Åström, K.J.: National bureau of economic research workshop on stochastic control and economic systems, Princeton 1972. |
| Report 7202 C | Åström, K.J.: Besök på Case Western Reserve University den 1 - 3 maj 1972 (Visit at Case Western Reserve University, May 1972). |
| Report 7203 C | Åström, K.J.: Reglerteknik i Holland, rapport från en studieresa 29 maj - 2 juni 1972 (Control engineering in Holland, travel report, June 1972). |
| Report 7204 C | Wieslander, J.: LOCUS, user's guide. |
| Report 7205 C | Ljung, L.: Reglerteknik i Sovjetunionen. Rapport från en studieresa 27 mars - 27 september 1972 (Automatic Control in the Sovjetunion, travel report, March - September 1972). |
| Report 7206 C | Holst, J.: Dead-beat reglering av värmestav (Dead-beat control of a heat rod). |
| Report 7207 C | Holst, J., and Ljung,L.: Systemanalys inom ekologin. Rapport över en kurs för ekologer i Uppsala (Systems analysis in ecology, Report from a course for ecologists in Uppsala). |
| Report 7301 C | Gustavsson, I.: Synpunkter på problem vid praktiska identifieringsexperiment - speciellt val av insignal (Some aspects of problem practical identification experiments - especially the choice of input signals) |

Report 7302 C Åström, K.J.: Några alternativa metoder för produktionsstyrning på Gruvön (Some alternative methods for production control at Gruvön)

Report 7303 C Åström, K.J.: Kontaktmöte med kraftindustrin vid institutionen för reglerteknik, LTH den 17 - 18 oktober 1968. (Contact meeting with the power industry at the Division of Automatic Control, October 1968)

Report 7304 C Eriksson, P.: Modell av torkpartiet hos en pappersmaskin (A model of the drying section on a paper machine).

Report 7305 C Åström, K.J.: Lectures on paper machine control

Report 7306 C Olsson, G.: Simplified models of xenon spatial oscillations.

Report 7307 C Ljung, L.: Comments on "A Stochastic Approximation Method"

Report 7308 C Olsson, G.: Möte med representanter för kraftindustrin på Sydkraft, Malmö den 1972-11-01 (A meeting at Sydkraft, Malmö, with representatives from the power industry).

Report 7309 C Leden, B.: Linear thermistor networks for temperature measurements.

Report 7310 C Åström, K.J.: A spectral factorization algorithm.

Report 7311 C — Söderström, T.: A program package for GLS identification of dynamic systems.

Report 7312 C — Söderström, T.: Programs for recursive identification.

Report 7313 C — Söderström, T.: A program for test of common factors of two polynomials.

Report 7314 C — Söderström, T.: Computation of asymptotic Least Squares estimates.

Report 7315 C — Söderström, T.: Programs for evaluation of identified models of simulated data.

Report 7316 C — Åström, K.J.: Ventiler och pumpar (Valves and pumps).

Report 7317 C — Möte med representanter för Ångpanneföreningen 20 februari 1973.

Report 7318 C — Andersson, L., Borisson, U., Braun, R., Syding, R.: A DDC-loop between Lund and Kiruna for control of an ore crusher.

Report 7319 C — Nilsson, L.: Försök med identifiering av snabba tidskonstanter. (Tests of identification of rapid time constants)

Report 7320 C — Burström, E.: Förkortning av gemensamma faktorer i skattade överföringsfunktioner. Kort beskrivning av programvaran. (Cancelling of common factors in estimated transfer functions. Short description of the programs).

Report 7321 C Nilsson, L.: Resultat från identifiering av testexempel för IFAC symposiet 1973 (Identification of test cases for the IFAC Symposium 1973).

Report 7322 C Åström, K.J., Hagander, P.: A fallacy on correlated white noise processes.

Report 7323 C Olsson, G., Ulmgren, L.: Reglering av avloppsreningsverk. Studieresa till USA och Canada 24 april - 16 maj 1973. (Control of wastewater treatment plants. A travel report from USA and Canada).

MS-THESES

RE-114 Svensson, G.: Dosplanering av läkemedel (Drug administration), August 1972.

RE-115 Borisson, J. and Brissman, J.: Undersökning av börvärdesjusterande regulatorer (Investigation of regulators for automatic adjustment of reference values), September 1972.

RE-116 Johansson, G. and Martinsson, G.: Modeller av ekonomiska system (Models of economic systems), October 1972.

RE-117 Kjellander, B. and Selander, S.: Balansförmåga mätningar och analys med processdator (Balancing capability on-line measurements and analysis), November 1972.

RE-118 Pehrsson, P-E.: Jämförelse mellan linjära och olinjära modeller för tankreaktorn (Comparison between linear and nonlinear models for a tank reactor), November 1972.

RE-119 Gabrielsson, P. and Luterkort, S.: Granulering-ett dynamiskt betraktelsesätt (Granulation in a fertilizer plant - a dynamical approach), November 1972.

RE-120 Lindberg, L.: Reelltidsidentifiering på Halden-data (Real-time identification of data from the Halden nuclear reactor), November 1972.

RE-121 Swärd, L. and Rasmusson, N-O.: Reglering av inloppslåda till en pappersmaskin (Head-box control on a paper-machine), December 1972.

RE-122 Persson, C.: Frekvensanalys (Frequency analysis), January 1973.

RE-123 Pettersson, O.: Analog simulering av en enkel pappersmaskinmodell (Analog simulation of a simple papermachine model), March 1973.

RE-124 Burström, E.: Förkortning av gemensamma faktorer i skattade överföringsfunktioner (Cancellation of common factors in estimated transfer functions), May 1973.

RE-125 Cronstedt, C.J. and Salmberg, L.: Identifiering av dynamiken i en granuleringsprocess (Identification of the dynamics of a granulating process), June 1973.

RE-126 Neiderud, B.: Tillståndsestimering i elkraftsystem (State estimation in power systems), June 1973.

RE-127 Mattsson, G.: Revidering av CSMP (A revised version of a CSMP package), June 1973.

RE-128 Kennedy, B.: Rotsyn - Ett program för syntes av linjära, tidsinvarianta system med rotortmetoden (Rotsyn - A synthesis program for linear, time invariant systems using root locus), June 1973.

RE-129 Ragnarsson, J.: Ekonomisk belastningsfördelning i kraftsystem (Economic load dispatch), August 1973.

RE-130 Folkesson, C.: Minimalvariansstrategier med begränsad styrsignal (Minimal variance strategies with limited control signal), August 1973.

RE-131 Thulin, J.: Datorreglering av en två-loops process med PID-algoritmer (Computer regulation of a two-loops process with PID-algorithms), August 1973.

## 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.

Linear Quadratic Control Theory (Div of Automatic Control)

Control Theory and Economic Policy (Div of Automatic Control and Economics Department)

Filtering Problems in Linear Infinite Dimensional Systems (Prof. R. Curtain, University of Warwick, Coventry)

Modelling of Dynamic Industrial Processes (Dr R. Isermann, University of Stuttgart).

### Seminars

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

Professor L.A. Zadeh, Univ of California, Berkeley, USA.

"Outline of a New Approach to the Analysis of Complex Systems and Decision Processes", September 19, 1972.

Professor A.H. El-Abiad, Purdue University, Indiana, USA.

"Different Power System Models", September 20, 1972
"Operating Control Schemes Based upon Optimum Load Flow", September 20, 1972.
"Security Functions Based upon Pattern Recognition", September 21, 1972.

Dr. J.M.C. Clark, Imperial College, London.

"On a Filtering Representation Theorem by Fugisaki, Kallianpur and Striebel", September 20, 1972.

Mr K. Wall and Mr M. Preston, Queen Mary College, London.

"Estimation and Transformation of Quarterly Model of U.K. Economy", September 21, 1972.

Dr F. Hartley, Cambridge University, Cambridge, England.

"Drying Control Problems in Paper Machines", September 29, 1972.

Mr L. Eriksson, STFI, Stockholm.

"Mätproblem och givarutveckling inom pappers- och massa-industrin" (Measurement problems and gauge developments in the paper and pulp industry), October 13, 1972.

Mr A. Garde, ASEA, Västerås.

"Hur vi löste reglerproblem på ASEA åren 1924-1947" (How control problems were solved at ASEA in 1924--47), October 24, 1972.

Professor J.H. Westcott, Imperial College, London.

"Estimation of a control model for the U.K. Economy", October 26, 1972.
"Development of Control Models for a Steal Cold Rolling Mill", October 27, 1972.

Mr T.W. Oerlemans, Shell Research N.V., Amsterdam.

"Economic Aspects of Computer Control", November 1, 1972.

Mr P. Schollander, KTH, Stockholm.

"Destillationskolonner" (Distillation columns), November 27, 1972.

Dr A. Ruhe, Umeå University.

"Numerisk beräkning av egenvärden till matriser - en översikt över uppnådda resultat och aktuella forskningsområden" (Numerical calculations of matrix eigen-values - a survey), February 2, 1973.

Mr G. Wästlund, IBM, Stockholm.

"Uppbyggnad av hierarkiskt processdatorsystem med IBM system/7" (Development of a hierarcical process computer system with the IBM s/7), February 16, 1973.

Mr U. Jaaksoo, Inst of Cybernetics, Tallin.

"Research at the Institute of Cybernetics in Tallin", March 1, 1973.

Mr H. Ramsin, KTH, Stockholm.

"Erfarenheter av kvasinewtonmetoder för minimering av reellvärda funktioner" (Experiences of quasi-Newton methods for minimization of real valued functions), March 30, 1973.

Mr L. Karlsson, Dataindustrier AB, Hägersten.

"Mikrodatorer" (Micro computers), March 23, 1973.

Professor J.B. Cruz, University of Illinois, Urbana, Illinois.

"Differential Games", April 5, 1973.

Professor T.G. Rogers, University of Nottingham, England

"A Continuum Theory for Fibre-reinforced Materials", April 17, 1973.

Mr T. Cegrell, ASEA, Västerås.

"Simulering av informationsöverföring i kraftnät" (Simulation of information transfer in power networks), May 3, 1973.

Mr A. Ramsheim, Gullfiber, Billesholm, and Mr P.E. Molander and Mr B. Karlsson, Sydkraft, Malmö.

"Datorer i reglersystem" (Process computers), May 14, 1973.

Professor J. Casti, University of Arizona, Tucson, Arizona, "Matrix Riccati Equations and Generalized x-y Functions", May 29, 1973.

"Imbedding Methods in Applied Mathematics", May 30, 1973.

APPENDIX F

LECTURES

The staff of the Division have given several lectures, and seminars during the year outside the University. Here follows a list of the most important ones:

Åström, K.J.,: System Identification. Invited "key-note" paper by K.J. Åström at the International Union of Theoretical and Applied Mechanics (IUTAM) Symposium, University of Warwick, July 10 - 14, 1972. Published in R. Curtain (editor) "Stability of Stochasitc Dynamical Systems", Springer Verlag, Heidelberg 1972.

Åström, K.J.: System Identification - A Survey. Invited paper given by K.J. Åström at the Royal Statistical Society Conference, Nottingham, September 1972.

Olsson, G.: Identification methods and their Applications to Nuclear Reactor Dynamics. Lecture held at the OECD Halden Reactor Project, Halden, Norway, September 8, 1972.

Wieslander, J.: Computer Aided Design Of Linear Feedback Regulators Using Linear Quadratic Control Theory. ONLINE 72. Uxbridge, September 1972.

Åström, K.J.: Stokastisk Reglerteori och Processidentifiering. Two lectures delivered at Tekniska Högskolan i Helsingfors, September 28 - 29, 1972.

Lindahl, S., Olsson, G., Åström, K.J.: Contact meeting with the power industry at Sydsvenska Kraft AB, November 1, 1972.

Hagander, P.: Några exempel på systemteknik inom bio-medicinen (Examples of biomedical control). Lecture held a seminar day on physiological systems, Linköping University, November 8, 1972.

Olsson, G.: Matematiska problem i reglertekniken (Mathematical problems in automatic control). Lecture held at the Royal Institute of Technology in Stockholm, January 31, 1973.

Gustavsson, I., Åström, K.J.: One day seminar on dynamic behaviour of steam power plants at Sydsvenska Kraft AB. At this meeting the main results were summarized of the works on steam power plant applications, mainly made by Dr Karl Eklund (now at the Axel Johnson Institute for Industrial Research). Identification results were also presented by Ivar Gustavsson and Karl Johan Åström, February 5, 1973.

Lindahl, S.: Presentation of application of optimal control theory to a simple power system model. Swedish State Power Board, Stockholm, March 9, 1973.

Hagander, P.: Reglerteknik och feedback i Naturens konstruktioner(Automatic Control and Feedback in Constructions made by Nature). Lecture held on a seminar evening arranged by SMR-Konstruktionskommittén, March 13, 1973.

Automatic control - Current theory, course for industrial people given in Lund, April 2 - 6, 1973.

1. Analys och syntes i tidplanet (Analysis and synthesis in the time domain (6 lectures by P. Hagander, Borisson, U.).

flyttas till (*)

Wieslander, J.: Interactive Programs For Computer Aided Design. Presented at "Computer Aided Control System Design" Conference, Cambridge, April 2, 1973.

2. Datorer som regulatorer (Computers as regulators (3 lectures given by B. Wittenmark)).

3. Analys och syntes med hänsyn till störningar (Analysis and Synthesis in a Stochastic Environment (4 lectures given by K. Eklund)).

4. Processidentifiering (Process Identification (3 lectures given by I. Gustavsson)).

5. Användning av optimeringsteori för syntes av reglersystem (Synthesis of control systems by optimization theory (4 lectures given by G. Olsson and S. Lindahl)).

6. Självinställande och adaptiva regulatorer (Self-tuning and adaptive controllers (2 lectures given by K.J. Åström and B. Wittenmark)).

(*) ⟶

Olsson, G.: Identification of nuclear power reactors dynamics from multivariable experiments. Lecture held at the University of California, Los Angeles, April 27, 1973.

Olsson, G.: Application of identification methods on nuclear reactors. Lecture held at Systems Control Incorporated, Palo Alto, California, May 2, 1973.

Hagander, P.: Biologiska reglersystem (Biological Control Systems) Two seminars given by P. Hagander at the Division of Automatic Control at Linköping University, May 10, and May 16, 1973.

Hagander, P.: Programbibliotek (Program library). Lecture given by P. Hagander at the Division of Automatic Control, Linköping University, May 9, 1973.

Eklund, K. and Gustavsson, I.: Identification of drum boiler dynamics, invited case study.

Wittenmark, B.: Results from the test cases - self-tuning control.

Gustavsson, I.: Results from test case A.

ter

Leden, B.: Halvledartermometern (The semiconductor thermome~~ter~~tre) Lecture by B. Leden on a graduate course: Elektriska givare för mätning av ickeelektriska storheter med elektriska instrument, Dept of Electrical Measurement, Lund Institute of Technology, May 3, 1973.

Mårtensson, K.: Optimal Temperature and Pressure Control of the Acid Sulfite Cooking Process. Brown University, Providence - MIT, Cambridge - Yale University, New Haven - University of Illinois, Urbana - Stanford University, Stanford.

Mårtensson, K.: A Constraining Hyperplane Technique for State Variable Constrained Optimal Control Problems. - Brown University, Providence, - 1973 Joint Automatic Control Conference, Columbus.

Mårtensson, K.: Differential Dynamic Programming Techniques. - Brown University, Providence.

Mårtensson, K.: Least Square Identifiability of Parametrized Dynamic Systems. - University of Southern California, Los Angeles.