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Process Control 1972-1973 : Final Report

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PROCESS CONTROL 1972-1973

FINAL REPORT

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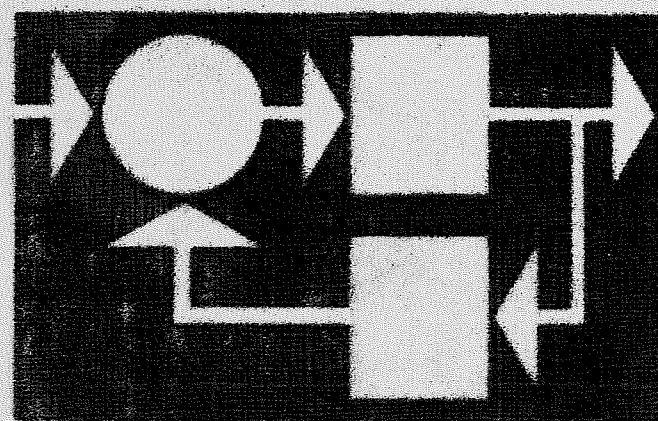
ABSTRACT

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 connec-
tion 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 Identifica-
tion and System Parameter Estimation in the Hague, 1973.
Out of 11 invited survey papers and case studies one sur-
vey 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 identi-
fiability 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 contem-
porary 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 asympto-
tic expression of the loss function, assuming an infinite num-
ber 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 mini-

mum 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 $A*(q^{-1}) = 1$ or 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 func-
tions 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 examp-
les 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.
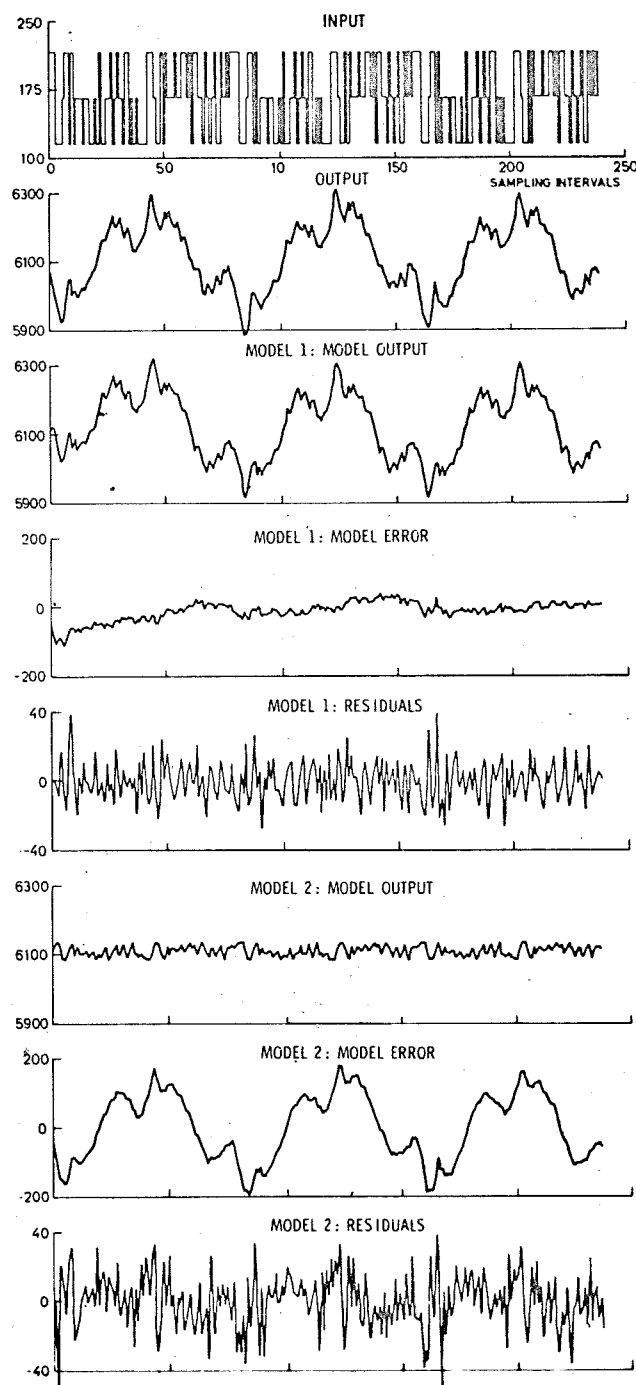
Models of the distillation column. Digi-
tal units are used. The sampling period
is 96 seconds.

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 num-
ber 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 esti-
mation.

Three different recursive schemes, all based on Extended
Kalman filtering, are tested and compared. Two of the
filters are ordinary Extended Kalman filters with diffe-
rent 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 exa-
mined for the test systems. The consistency of the esti-
mates is another problem. Bias and parameter variance are
examined and compared to the assumed statistics.

It is shown that the information available when the fil-
tering is performed has a negligable influence on the bias
and parameter variance in the long run. However, the artifi-
cial 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 fil-
ters.

Several numerical problems have arisen in the filter algorithms
especially for extremely large errors of the parameter ini-
tial 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 estima-
tion 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 non-
linear 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 α 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 α. 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 non-
linear model for a drum boiler, Eklund and Gustavsson
(paper 1973).

The interactive program for the multiple input single out-
put 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 fre-
quency interval, measuring time etc. The computer then gene-
rates 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 para-
meter 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 experi-
ments. 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 treat-
ment 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 per-
formed 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 pre-
viously mentioned conference paper by Lindahl - Ljung (paper
1973).

As an example of a non-conventional application the identifi-
cation techniques have been used to determine the thermal
diffusivity in copper in a much more accurate way than be-
fore, 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 regula-

tor. There are about 4 operations (additions and multi-
plications) 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 estima-
tion 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 dead-
beat 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 ob-
tained 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 mathe-
matically. 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 diffi-
cult 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, how-
ever, 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 multi-variable 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 Θ_n of the identification depends on the feed-
back law. This in turn depends on the estimate. The se-
quence of parameter estimates can therefore be described
by a non-linear, time-varying stochastic equation

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

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

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

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 conver-
gence of the self-tuning regulator has been established for
certain classes of systems. Also, the counter examples men-
tioned above, where the self-tuning regulator does not con-
verge, 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 re-
gulator are reported in Wittenmark (report 7311). Theo-
retical 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 sub-
routines 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 uncon-
strained 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 pre-
sented 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 in-
sight 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 build-
ing. 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 im-
provements 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 proceded 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) re-
   sulted 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 trans-
   fer 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 se-
quence 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 graduate 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 im-
portant to understand clearly the difference between
various inverses, particularly their stability pro-
perties. 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 feed-
back structure, e.g. due to constraints in measured sig-
nals or information exchange. This means that only output
or restricted output feedback is permitted, where each out-
put 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 struc-
ture, (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 tech-
niques 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 gene-
rators indicates that the proposed method is feasible. The
reduced feedback law does not require any information ex-
change.

In connection with real-time control of power systems much
interest has been devoted to the power system state estima-
tion problem. To apply modern filtering theory to this prob-
lem 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 assump-
tion 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 esti-
mator 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 dif-
ferential 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. Further-
more the evaluation of the data has been performed using
our identification programs, mainly the interactive identi-
fication 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).

<u>Adaptive control of a paper machine (U. Borisson and B. Wittenmark).</u>

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 ex-
periments.

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 con-
siderable 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 ex-

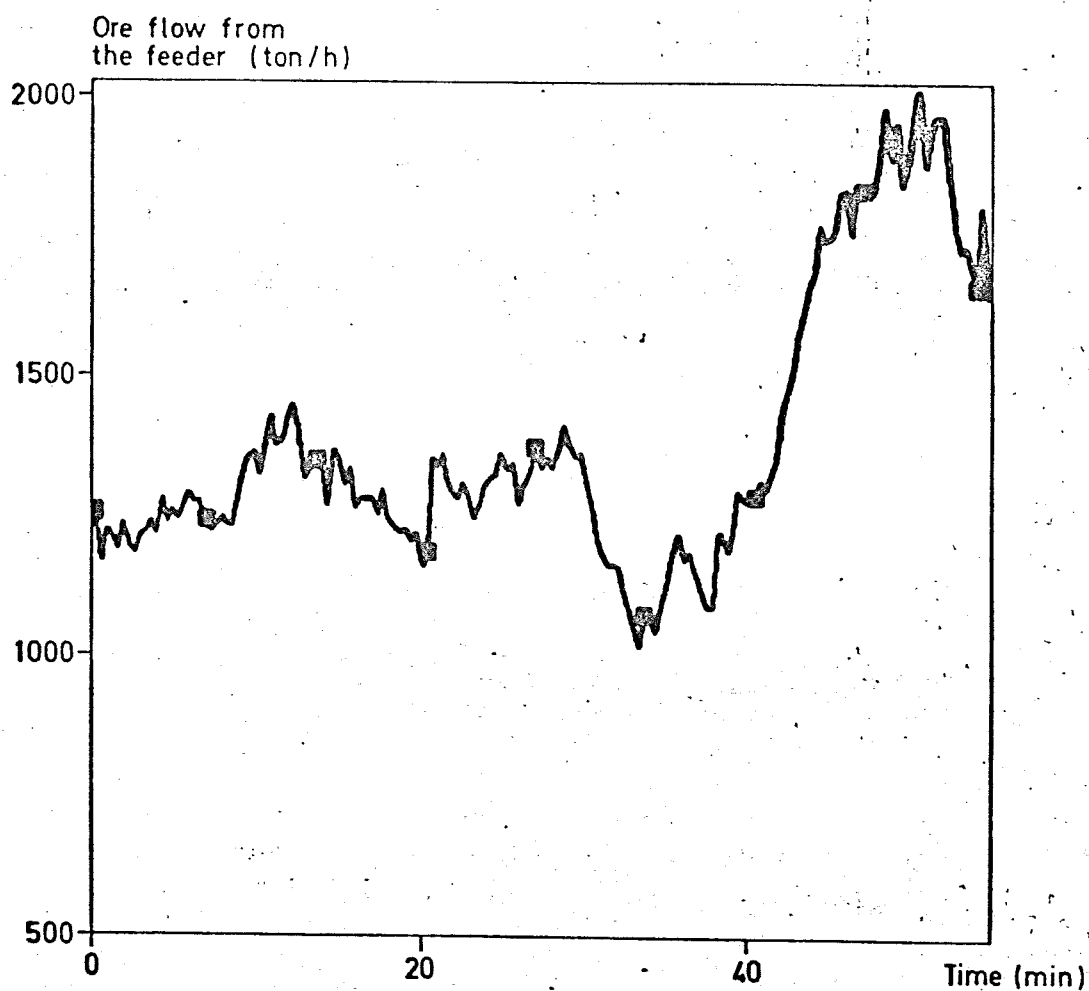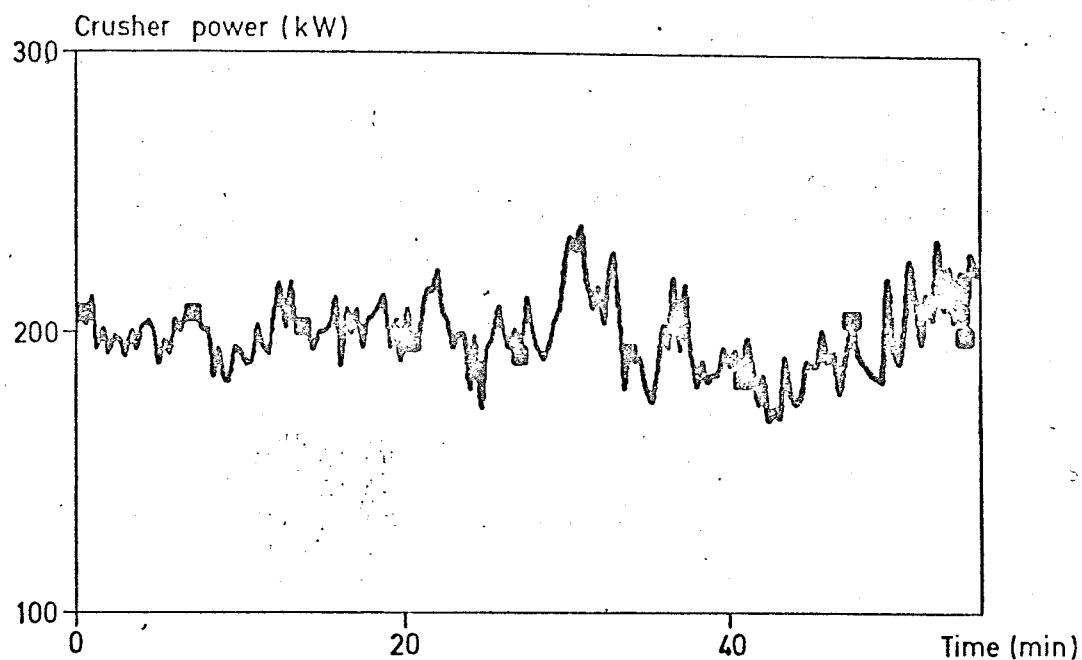periences from the use of tele-processing for remote control were good.

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 head-
ing are the outputs, are estimated and the results are pre-
sented in Åström - Källström (paper 1973a). In this paper
the ideas behind the new program package for parameter esti-
mation 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 Develop-
ment (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 Hydrau-
lics, 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 per-
formed at the pilot plant at the Sjölunda wastewater treat-
ment 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 recircula-
ting 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 con-
trol.

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 rea-
listic 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 instrumen-
tation 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 investi-
gated. 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 accep-
tance as an accurate method for determining the thermal dif-
fusivity. 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 measure-
ments 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 func-
tion 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 or-
dinary 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 pub-
lished in Leden et.al. (paper 1973). This study was per-
formed 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 com-
pleted 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

4 logical outputs. The output part of the system and ten
termistor bridges for temperature measurements were con-
structed and built. Programs that are necessary to communi-
cate 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 condi-
tions 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.
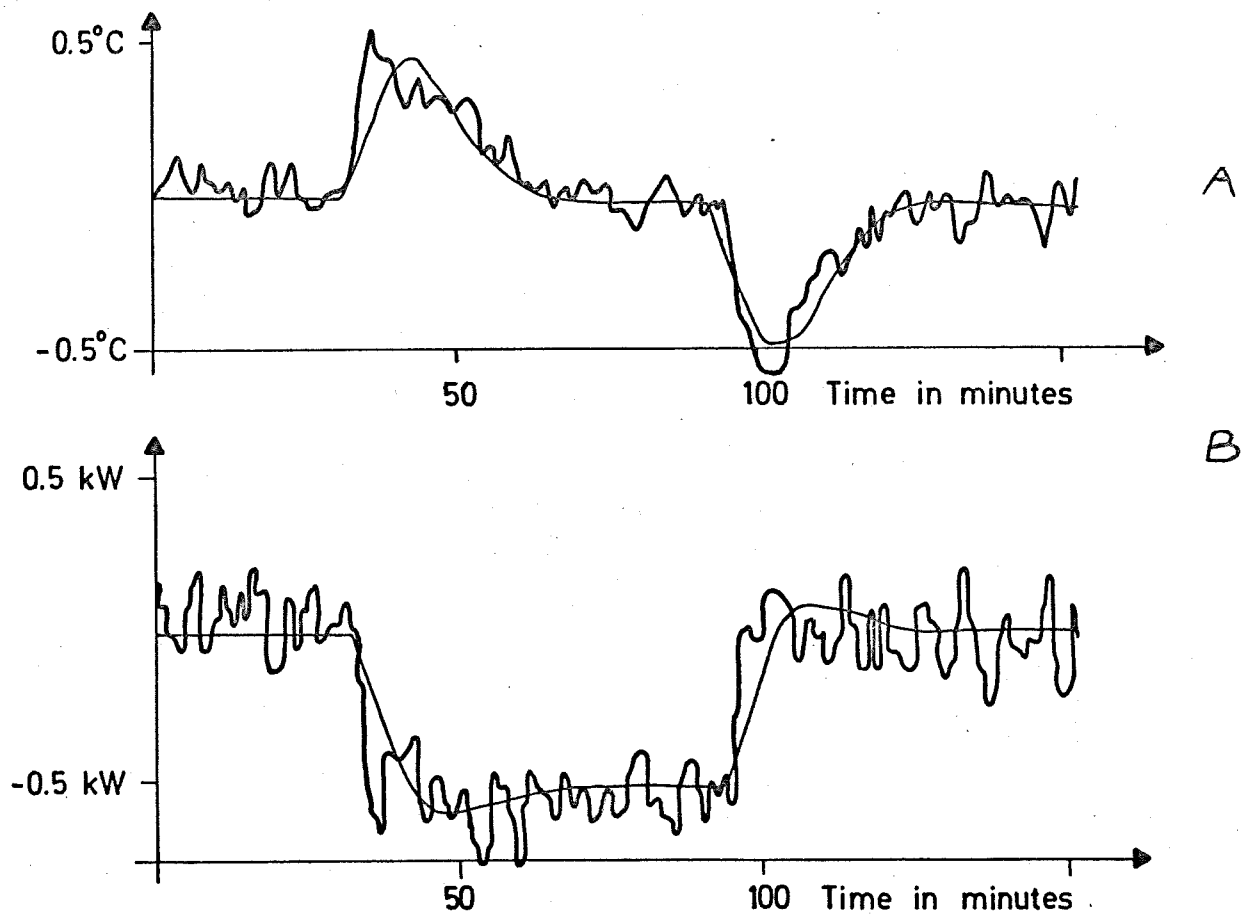
Figure 7.2 - Comparison between simulation and experimental results when using a fourth order regulator based on the identification results. A: Thin line: Simulated temperature. Thick line: Experimental result. B: Thin line: Simulated input signal. Thick line: Experimental result.

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 build-
ings 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 estima-
tion 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 identifi-
cation techniques to macroeconomic modelling. This is re-
ported 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 Thålberg 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 on-line 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 diffi-
cult 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 de-
cay. 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 fea-
sibility 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 condi-
tions 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 multi-
variable 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 mo-
dels 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 Depart-
ment 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 regula-
tors 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 docu-
mented 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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leringsprojektet för år 72/73, Lund, January 1972.

LIST OF PERSONNEL

Professor	Karl Johan Åström
Universitetslektor	Gustaf Olsson
"	Björn Wittenmark
Forskningsingenjör	Leif Andersson
"	Ivar Gustavsson
"	Lars Jensen
"	Claes Källström
"	Staffan Selander
"	Johan Wieslander
Assistent	Gunnar Bengtsson
"	Ulf Borisson
"	Bo Leden
"	Sture Lindahl
Forskningsassistent	Per Hagander
Forskarassistent	Lennart Ljung
Lab. ingenjör	Rolf Braun
Doktorand	Hilding Elmqvist
"	Torkel Glad
"	Jan Holst
"	Jan Sternby
"	Torsten Söderström
Tekniskt biträde	Bengt Lander
"	Birgitta Tell
Rithjälp	Karina Bolinder
Sekreterare	Eva Schildt
"	Walburga Schultz
Skrivhjälp	Gudrun Christensen
"	Kerstin Palmqvist

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Report 7222   Roggenbauer, H., Seifritz, W. and Olsson, G.:
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Report 7223   Olsson, G.: Power-Nuclear Plants, September 1972.

Report 7224   Åström, K.J.: Properties Of The Equations De-
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Report 7225   Bengtsson, G. and Lindahl, S.: A Design For In-
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Report 7226   Keviczky, L.: On Some Questions Of Input Signal
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                Systems - A Survey Introduction, Januray 1973.

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Report 7303   Hagander, P.: Initializing A Kalman Filter When
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Report 7304   The Report was nerver published.

Report 7305   Bengtsson, G.: Minimal System Inverses For Linear
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Report 7306   Söderström, T. and Åström, K.J.: Uniqueness Of
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                meters Of A Mixed Autoregressive Moving Average
                Process, March 1973.

Report 7307   Söderström, T.: On The Uniqueness Of Maximum
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                tures, March 1973.

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

Report 7309   Källström, C.: Computing Exp(A) and $\int$Exp(As)ds,
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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 Identi-
                fication In Chemical And Physical Processes,
                March 1973.

Report 7314   Söderström, T.: Uniqueness And On-Line Algorithms
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Report 7315   Hagander, P.and Johansson, L.: Incompatibility
                Alleles; Characteristics Of A 1-locus System,
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Report 7316   Olsson, G.: Modelling And Identification Of
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                Experiments, April 1973.

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

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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.

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TECHNICAL REPORTS (internal)

Report 7201 C   Åström, K.J.: National bureau of economic
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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,
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Report 7204 C   Wieslander, J.: LOCUS, user's guide.

Report 7205 C   Ljung, L.: Reglerteknik i Sovjetunionen.
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Sovjetunion, travel report, March - September
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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, Re-
port 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 alterna-
                 tive 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 Approxi-
                 mation Method"

Report 7308 C   Olsson, G.: Möte med representanter för kraft-
                 industrin på Sydkraft, Malmö den 1972-11-01
                 (A meeting at Sydkraft, Malmö, with representa-
                 tives 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 Ångpanneföre-
                 ningen 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 identifica-
                 tion 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 func-
                 tions. 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 av-
loppsreningsverk. Studieresa till USA och
Canada 24 april - 16 maj 1973. (Control of
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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 re-
          ference 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 inlopps-
          låda 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 fak-
         torer i skattade överföringsfunktioner (Can-
         cellation of common factors in estimated trans-
         fer functions), May 1973.

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

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

RE-127   Mattsson, G.: Revidering av CSMP (A revised ver-
         sion 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 be-
         gränsad 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.

<u>Mr A. Ramsheim</u>, Gullfiber, Billesholm, and Mr <u>P.E. Molander</u>
and <u>Mr B. Karlsson</u>, Sydkraft, Malmö.

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

<u>Professor J. Casti</u>, 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 Insti-
tute 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 kon-
struktioner (Automatic Control and Feedback in Construc-
tions 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.).

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 regler-
   system (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
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