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FINAL REPORT FOR PROJECT PROCESS  
CONTROL 1.7 1968 - 30.6 1969  
CONTRACT 68-336-f SWEDISH BOARD  
FOR TECHNICAL DEVELOPMENT

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FINAL REPORT FOR PROJECT PROCESS CONTROL 1.7.1968 - 30.6.1969  
CONTRACT 68-336-f SWEDISH BOARD FOR TECHNICAL DEVELOPMENT

K.J. Åström and G. Olsson

#### ABSTRACT

This report covers the second year of the project process control at the Division of Automatic Control at Lund Institute of Technology. The research has been divided into four fields: Process Identification, Numerical Methods for Optimal Control, Adaptive Control and Applications - mainly Thermal Boilers and Nuclear Reactors. Apart from the progress made in these areas the report also covers some efforts that have been made to promote the applications of the results to industrial problems.

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## 1. INTRODUCTION

The project is part of a long range program in the area of process control. A program covering a period of three years is given in [1]. The results obtained during the first year is reported in [2]. This report covers the results obtained during the second year. A detailed program for this is given in [3]. We have essentially been able to follow the plans. The only major difference is that we have devoted much more effort to practical industrial applications of process identification than was anticipated in the plans. This has had the consequence that theoretical work on nonlinear identification has been somewhat delayed. Based on the results obtained we have also formulated a new three year program [4] with detailed plans for the year 1969/70 [5].

All research activity at the Institute has been centered around the process control project. Contributions have been given by the three research engineers supported by the Swedish Board of Technical Development (STU) as well as students and staff of the Institute. The work has been organized so that the research engineers have acted as project leaders in the areas: Process Identification, Numerical Methods of Optimal Control and the Boiler Control Project. The major coordinating function has been done by Gustaf Olsson and Karl Johan Åström. This report covers the total activity on the process control project also parts which are not directly supported by STU.

## 2. PROCESS IDENTIFICATION

This work has had a dual purpose to obtain models and to get insight into the properties of different identification schemes. The main effort has been devoted to measurements of nuclear reactor dynamics in collaboration with AB Atomenergi and distillation column dynamics in collaboration with National Physical Laboratory in England. The collaboration with AB Atomenergi is a direct result of the contact meeting held in Lund in December 1967.

Some progress has also been made in the area of real-time identification. A real-time version of the maximum likelihood estimation (MLE) method has been developed. Simulations indicate that the method is asymptotically efficient for first order systems. For systems of higher order, however, this does not seem to be the case. The reason for this is not yet clearly understood.

We have also started a collaboration with the Institute of Information Theory of the Academy of Sciences in Prague, and we have at present a guest worker Jaroslav Valis from the Institute.

### 2.1 Identification of linear process dynamics (I. Gustavsson)

The program package for maximum likelihood identification of disturbances and linear process dynamics has been tested with artificially generated data and has also been used for identification of several industrial processes. The description of the program package is given in a report [C:17]. The results of the identification with the maximum likelihood method have been compared with results obtained with various other identification methods, for instance correlation analysis and least squares estimation.

Programs for identification of linear dynamics from the impulse response have been written [D:RE53].

Problems requiring further investigation have appeared during these studies. For instance it has turned out that the ordinary spectral analysis tends to give a remarkable error in the estimates of the phase, even far below the Nyquist frequency. Furthermore the least squares method often gives a high order model, even when the disturbances seem to be small. Strongly correlated measurement noise cannot be easily detected direct from the output signal, which even in the presence of such noise is smooth. Thus it may be difficult to choose identification method only by observing the input/output sequences.

Processes which have been studied are among others nuclear reactor dynamics [C:13], evaporation [D:RE36], distillation, drying section of a paper machine [D:RE42]. Data have been received from AB Atomenergi, Studsvik, Perstorp AB, Perstorp, National Physical Laboratory, London, and Billerud AB, Billerud. For most of the applications the different identification methods have given comparable results. The models seem to be reasonable according to the a priori knowledge of the processes.

In some cases, however, certain differences between the results from the different identification methods have been found. These problems have been studied by identification of artificially generated data. The identification of industrial processes has given important information on what problems that can arise in such cases. Examples of such problems are choice of input signal, sampling interval, structure of the model and identification method. Some insight in the effect of the choice of sampling interval has been provided [C:7].

When using the maximum likelihood method two problems arise. One of them is to choose the appropriate order of the model, the other is to choose the appropriate time lags. Furthermore if the process has several inputs it will be difficult to simplify the obtained model. For none of these cases the available statistic tests seem to be quite satisfactory. They seem to give models with too many parameters. Until now only one multivariable system has been investigated, the drying section of a paper machine [D:RE42].

Preliminary contacts have been taken with several other companies and these contacts will probably result in a number of practical applications of the available identification methods. The identifications techniques developed now seems to have reached a reasonable state of maturity so that it seems worthwhile to spread their use.

## 2.2 Real-time identification (J. Wieslander)

Identification methods can be divided into three groups regarding their way of operation.

- off-line methods e.g. the ML-method
- on-line method e.g. recursive least squares
- real-time identification methods

The main feature of the real-time methods is their ability to track the parameters of time-varying systems. The knowledge of the values of the system parameters in real-time is of great importance in the design of adaptive controllers.

The activities of the Institute concerning real-time identification algorithms has been focused at the Kalman filter approach. The algorithm obtained in this way has been implemented on various computers with encouraging results with respect to core-requirements as well as computing times.

The algorithm has been tested on simulated data with good results. This experiment was demonstrated at a seminar on identification methods for industry people in October 1968 [F:1].

Experiments on industrial data has been and is being made on data obtained from measurements on a paper mill dryer.

A difficult and important problem is that of stability of the estimator algorithm. To gain insight into the behaviour of the algorithm simulations on a hybrid computer has been made.

The results mentioned above will be described in [C:18] and [C:19]. A method for real-time identification using least squares techniques was described in [C:10].



### 3. ADAPTIVE CONTROL

The area of adaptive control has been pursued with a relatively low priority. Several exploratory investigations have been performed. As a result of this we have now definite plans for a more extensive research in the year 1969/70. See [5]. Different adaptive schemes proposed in literature have been compared.

#### 3.1 Theoretical studies (B. Wittenmark)

The idea of formulating the adaptive problem as an optimal control problem for a markov process has been pursued. The character of the solutions of the functional equations obtained have been investigated. [C:5].

It has also been demonstrated that a reasonably large class of adaptive processes can be represented by the following Markovian model

$$x(t+1) = Ax(t) + Be(t)$$

$$y(t) = Cx(t)$$

where  $e(t)$  is gaussian noise and  $C$  is a function of the control signal  $u(t)$ . The purpose is to control the system so that

$$V(N) = E \sum_{t=1}^N (y_{\text{ref}} - y(t))^2$$

is as small as possible.

Many of the phenomena found in adaptive systems have been observed also in this simple model.

Suppose  $y_{\text{ref}} = 0$ , the system is of second order and  $C = [1 \ u(t)]$ , then

$$V(N) = E \sum_{t=1}^N (x_1(t) + u(t) x_2(t))^2$$

If  $x_1(t)$  and  $x_2(t)$  were known exactly the lossfunction would be zero with the control strategy

$$u(t) = - \frac{x_1(t)}{x_2(t)} \quad (1)$$

Now since  $x_1$  and  $x_2$  are not known they have to be estimated. Using a Kalman filter as estimator, a possible control strategy is

$$u(t) = - \frac{\hat{x}_1(t|t-1)}{\hat{x}_2(t|t-1)} \quad (2)$$

where  $\hat{x}_1(t|t-1)$  and  $\hat{x}_2(t|t-1)$  are estimates of  $x_1(t)$  and  $x_2(t)$  based upon observations up to time  $t-1$ .

The strategy (2) is not a good one if the estimates are poor and if  $\hat{x}_2$  is near zero, then it sometimes gives a greater lossfunction than no control at all.

Next look at just one step. Minimize

$$V' = E\{x_1(t) + u(t)x_2(t)\}^2 | y(t-1), y(t-2) \dots\}$$

Now it can be shown that

$$V' = (\hat{x}_1(t|t-1) + u(t)\hat{x}_2(t|t-1))^2 + u(t) p_{12}(t) + u^2(t) p_{22}(t)$$

where  $p_{12}(t)$  and  $p_{22}(t)$  are elements in Kalman's variance matrix. Minima is obtained for

$$u(t) = - \frac{\hat{x}_1(t|t-1)\hat{x}_2(t|t-1) + p_{12}(t)}{\hat{x}_2(t|t-1)^2 + p_{22}(t)} \quad (3)$$

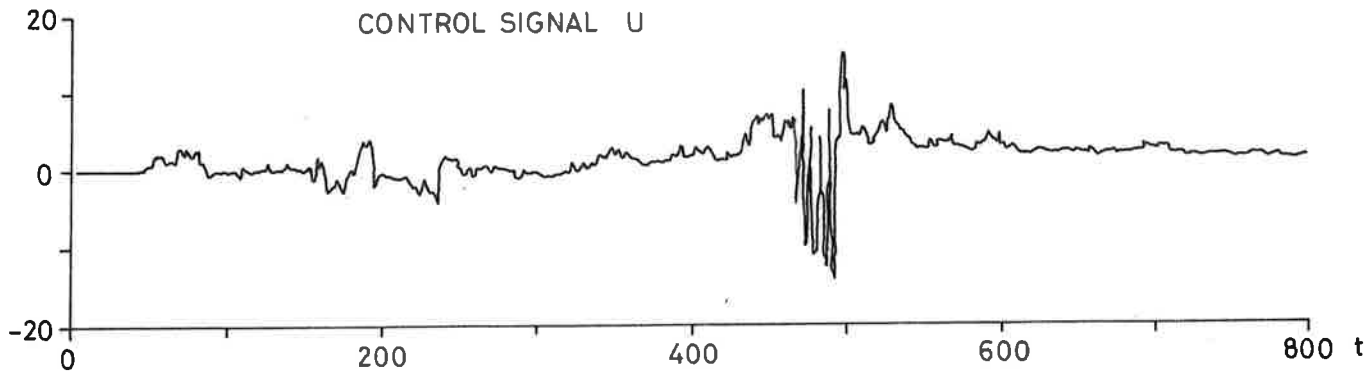
If the variance is zero, e.g. if the estimate is exact, (2) and (3) give the same control law.

As (3) only minimize for one step this control law does not make anything to get better estimates. This type of control is called non-dual.

A control law which also acts to get better estimates is called dual control. To get a dual control one have to iterate the lossfunction backwards using a Dynamic Programming technique.

When using the nondual control law one sometimes can get strange results.

- The controller gives up and puts  $u(t)$  almost to zero
- $u(t)$  is almost zero for long time. After many timesteps the regulation turns on again and we get a proper control.
- Burst phenomena, this is best shown with a figure.



These phenomenas are not complete understood yet, but we have through simulation got a good insight.

### 3.2 Comparison of different adaptive schemes

The work with investigation of implemented adaptive regulators has continued. The Minneapolis-Honeywell regulator earlier described by Syding and Sogndahl [D:RE20 and D:RE26] has been further investigated through digital simulation. The regulator was easy to implement on a digital computer and the subroutine contained only about 15 FORTRAN statements. The results of the digital simulations were compatible with the results obtained with the analog version of the regulator [D:RE41].

#### 4. NUMERICAL METHODS FOR OPTIMAL CONTROL

Two main projects have been pursued. Subroutines which can be used in a package for automatic synthesis have been developed and analysis of the numerical problems associated with the solution of the Riccati equation has been worked out. Much of the work has been done as a direct result of practical problems in the applications projects. Some interesting numerical experiments have also been done in the area of large systems. A list of programs presently in use is given in Appendix E. The programs will not be finalized until the computing Centre in Lund has the new computer installed.

##### 4.1 Computer programs for synthesis (P. Hagander)

A package for solving linear systems of equations and for inversion of matrices, recommended by Forsythe, has been coded, and test programs are written.

The main idea of the package is that inversion of a matrix is seldom necessary. The matrix  $T^{-1}Q$ , for instance, is from given  $T$  and  $Q$  best computed by solving the system  $T x_i = q_i$ , where  $q_i$  are the columns of  $Q$  and  $x_i$  are the columns of the wanted matrix  $T^{-1}Q$ .

Subroutines and test programs for transformations of a linear dynamic system  $S(A,B,C,D)$  are coded and applied to various samples. The routines can also be used to obtain the transfer function and to test observability and controllability for both single and multivariable systems. The fact that observability and controllability (reconstruction and feedback) are dual problems has simplified the package very much.

##### 4.2 Large systems

The intention is to find out where the difficulties with large systems do occur, when the accuracy in the computing methods no longer is enough. The heat equation in one dimension is simulated on a digital computer with models of various order, and the step and impulse response are calculated by means of series

expansion of  $\exp(A \cdot h)$ . Astonishing few difficulties arise, probably because the A matrix has no elements outside the super and subdiagonals and is extremely stable.

If the model is transformed to companion form (corresponding to the transfer function) a significant loss of accuracy occurs. This is an important result, and it might be valuable for the choice of structure in identification, for example. It will be further investigated. In this area has also been written a MS thesis on decomposition of large systems [D:RE46].

#### 4.3 Time optimal control of a nonlinear system

For the problem to raise a pendulum in minimum time by horizontal acceleration of the pivot point (absolutely constrained control) is a strategy deduced by intuitive reasoning. It is also proved that this control fulfills the Pontryagin necessary conditions for optimality. (Report to appear).

#### 4.4 Linear quadratic control package (K. Mårtensson)

The development of program packages for linear quadratic control has now been completed. In the report [C:14] algorithms for the solution of the sampled problem are presented. Typical usage of the sampled version is the implementation of optimal control on process computers. The program has been used to design regulators and filters for a boiler. See section 5.

The sampled version together with the previously published continuous version [C:2] is a powerful tool to design regulators for multivariable systems. Some MS theses [D:RE38] have been initiated to examine further possibilities to use linear quadratic theory in the design of control systems.

The so called Riccati equation

$$-\frac{dS}{dt} = A^T S + SA - SBQ_2^{-1} \cdot B^T S + Q_1$$

plays an important role in the linear quadratic theory. Analysis of this equation has made it possible to extend the theory to

more general cases. These results will be presented in a report to appear.

Studies have also been carried out concerning the possibilities to design suboptimal regulators. This is important when dealing with systems of very high orders e.g. distributed systems.

## 5. APPLICATIONS

The main effort has been devoted to control of thermal boilers. The boiler project has been completed during the year. The result has been a method for mathematical modeling and a scheme for digital control of a boiler which has been simulated on the hybrid facility of the Research Institute of National Defense. We have also taken several steps in order to find new projects in the area. It is our opinion that unless experimental data can be obtained, it is of no use to persue the theoretical work further. In collaboration with Sydkraft we have therefore in June this year carried out identification experiments on a 160 MW aggregate. (This is a direct result of the contact meeting with power industry in October 1968).

In collaboration with Kockums AB we have also planned experiments on a marine boiler.

The models of thermal power stations could also be very useful in connection with studies of power systems.

Apart from the boiler project we have also investigated spatial oscillations in nuclear power reactors.

An extensive evaluation of process control computers has also been done in connection with the planning of an experimental facility.

A thermal experimental system has also been planned and the building initiated.

### 5.1 Thermal boilers (K. Eklund)

Linear models of the drum-downcomer-riser loop have been developed. The models are described in [C:9].

This report presents a comparison with the dynamic properties of linear models of different order. The influence of some physical parameters on the model dynamics has also been investigated. The model is a FORTRAN program and input data is construction data for the boiler. In a MS thesis [D:RE48] the model has been expanded with two superheaters and one desuperheater.

In cooperation with Kockums Mekaniska Verkstad measurements will be made on the drum boiler of a tanker. These measurements will be used for the identification of the dynamics of the boiler. The work has been initialized and the measurements are planned to be made during October-November 1969. In cooperation with Sydsvenska Kraft AB similar measurements have been made on a 160 MW power station boiler during June 1969. A MS thesis work to derive a model from physical equations for this boiler has been made [D:RE55]. This work uses the earlier developed models.

A comparison between models based on physical equations and measurements will alighten the possibilities to derive reliable dynamic models from construction data.

The control of the drum pressure and drum level has been studied. The control laws developed are based on linear quadratic control theory. The control law also included a Kalman filter for the estimation of the state variables. The load disturbances were modelled from measurements as a stationary stochastic process. The control situation was simulated on a hybrid computer. These simulations gave valuable information of the sensitivity of the Kalman filter to parameter variations.

The boiler studies have given some special results concerning the model building technique.

#### Numerical model building

It is a very tedious work to develop a mathematical model of an industrial process of some complexity. The work usually involves the following steps:

- Describe the process by basic physical equations
- Compute steady-state solutions
- Linearize system equations
- Reduce linearized equations to state space form  $\mathcal{S}(A,B,C,D)$

The first step is often the least time consuming one. The work to carry out the three last steps is, however, very extensive. A systematic approach to the modeling problem which allow a computer to do all the tedious work was developed. The results are presented in [C:8].



It is also interesting to note the connection with numerical identification. For example badly known equations could be identified and physical equations could be used otherwise.

### 5.2 Spatial instability in nuclear power reactors (G. Olsson)

In large nuclear power reactors there is a spatial stability problem depending on the fission product xenon, which has a very big neutron cross section. Stability is affected by parameters such as core size, flux level, spectrum and temperature feedbacks. In this study the axial stability of pressurized water reactors is focused. The purpose has mainly been to analyze the influence of nonlinear terms, such as control rods and temperature feedbacks. In order to solve the space-dependent equations the core is first divided into two parts, why the xenon process can be described as a fourth order nonlinear system. In the linear approximation and for symmetric equilibrium flux two of the eigenvalues are independent of core parameters. The two remaining eigenvalues can be studied analytically by a second order submatrix. When the number of core meshpoints is increased the stability boundary for 20 meshpoints can be extrapolated out of 2, 3 and 4 meshpoints within an accuracy of a few percent.

The nonlinear behaviour of the two-point model shows both stable and unstable periodic solutions as well as a very strong dependence on rod configuration. This behaviour has been completely verified by digital simulations of a nonlinear model, written earlier [C:20].

A number of computer simulations has been supplemented to the analytical studies [C:21].

### 5.3 Evaluation of process computers (G. Olsson)

An extensive evaluation of process computers has been done during the year [C:22]. In [4] is presented the projects which will be worked out on the computer. In order to fit the requirements from different applications, which are planned we made a detailed specification list of hardware and software. The

main specifications were high internal arithmetic capacity, a disc system, high level language and a disc oriented monitor.

The preliminary study included over twenty computers. The manuals and prices were studied and interviews were made to those who have experiences on different computers. A meeting with industrial people was held one day in April 1968 where process computer problems were discussed. About ten computers remained after this study.

The next stage was a test of the internal capacity of the computers. A number of tests of standard routines and applications were run on different computers and computing times were compared. It was found that the efficiency of the FORTRAN compilers for certain routines varied considerably between different computers and that some compilers did not use the available hardware efficiently.

As a disc system is essential for our applications we continued by testing the system of one computer which was available. As the other disc systems were not available in Sweden, we had to study manuals only.

Twelve computer firms were asked for quotations. Eight of them answered. PDP 15-30 was the cheapest computer, which fulfilled the specifications. The computer is supplied with a fixed head disc and analog input-output channels. It will be delivered in March 1970.

The study of process computers has been extended to the whole small computer market in Sweden. The market is extremely expensive and a report in this area is never quite actual but [C:22] gives the state just now.

#### 5.4 Thermal rod system (B. Leden)

A thermal system representing a partial differential equation will be examined experimentally tied to a process computer. Problems in the area of identification and control of multi-variable and infinite order systems shall be examined.

The system consists of a metal rod where temperature can be controlled by regulators at the ends. The temperature can be measured in different points of the rod by thermistors.

The electronic equipment required has been built up around the system. The temperature which is measured by thermistors is converted to electric voltage between plus and minus 5 volts, corresponding to  $20^{\circ}$  -  $30^{\circ}\text{C}$  temperature interval, with an error of  $0.02^{\circ}\text{C}$ .

The temperature regulators consist of two Peltier-elements placed on each side of a silver wedge. The elements are connected to a power amplifier via a PID-regulator.

It is possible to get a temperature rise of  $1^{\circ}$  in 4 sec at the boundary.

## 6. CONTACTS WITH INDUSTRY

The industrial development in the area of control is presently in a very dynamic stage, mainly due to the advent of cheap process control computers. A close contact with industry is judged to be very valuable both for us and for them. The major motivations are

- to provide industry with hints from theoretical tools presently available
- to give a realistic foundation for theoretical work
- to find new problems

It is our policy to act vigorously in order to contribute towards bridging the gap between theory and practice.

Several forms of contacts have been tried

- courses
- contact meetings ("kontaktdagar")
- joint projects
- trips

### 6.1 Courses

Two courses for industrial people have been given during the year. In October a two days course on identification was held in Lund in collaboration with "Svenska Teknologföreningens avdelning för reglerteknik". About forty persons participated. The program is given in [F:1] and a brief report in [F:2].

In March a four days course was held by the Institute in Rättvik. The course was arranged by "Svenska Teknologföreningen (STF)". It had the theme "Reglerteorier i omdaning" (New Ideas in Control Theory). The interest for the course was very high from the industry and about sixty attendants came. The same course is already planned to be held in next spring. The program is presented in [F:3].

## 6.2 Contact meetings

In order to establish new contacts with industry we have tried a system with contact meetings in Lund. Up to now we have had four meetings which have been successful. Several concrete results have come out of the meetings.

Three of the meetings were held before 1.7.1969 but are mentioned because of the works which have been done after them [F:4]-[F:5].

In cooperation with Sydkraft (see section 5.1) measurements on a 160 MW boiler have been made. Problems from Sydkraft on production planning have also been treated in three MS-theses works (see section 6.3). AB Atomenergi has provided data from Ågesta nuclear reactor for identification (see section 2.1).

One meeting was held during the preliminary study of process computers in April 1968. Users from industry were present and computer problems in control were discussed.

In October 1968 [F:6] a contact meeting with power industry people was held during two days. Swedish State Power Board, Sydkraft, AB Atomenergi, OECD Halden Reactor Project and ASEA were represented. As a result of the meeting we are going to tackle problems in power distribution. The cooperation with Sydkraft and AB Atomenergi is already mentioned. With Halden we have already got experimental data which now are analyzed. With ASEA there are several projects going on (see section 6.3).

## 6.3 Joint projects

### 6.3.1 ASEA

A problem on container handling has been proposed by ASEA. This is an interesting application on nonlinear control theory and has also a big commercial interest. The problem is to find how a container should be moved from for example a quai to a storage place in minimal time due to all constraints which may appear. The job will be done by Krister Mårtensson.

### 6.3.2 ASEA-ATOM

In large nuclear power reactors there is a strong need to know the power distribution in the core more exactly than is possible today. One wants to find a way to mix measurements from the in-core detectors with theoretical calculations. The problem was studied in detail during a week in August 1968 by Gustaf Olsson. It was found that Kalman theory offers a solution but the very high dimensionality of the problem offers tremendous numerical problems. The problem is going to be studied in smaller scale in the laboratory at the process computer and the thermal rod system.

### 6.3.3 Billerud AB

The Institute has a joint connection to Billerud AB through a techn.lic. thesis work, being done by Bengt Pettersson. Optimal control theory has been found to be very useful to solve production planning problems. The problem is to find the best way to run the chemical and other preparatory processes before paper machines with respects to planned interrupts in the factory.

During one month February 1969, Gustaf Olsson visited the factory at Gruvön when the production planning system was to be implemented at the process computer IBM 1800. At the same time measurements were made on a paper machine in order to identify the dynamics on the drying section. It has resulted in one MS thesis [D:RE57].

### 6.3.4 Billman Regulator AB

In cooperation with Billman has been made measurements temperature in different parts of a house in Malmö. Identification analysis of the dynamics from heat exchanger to the flats has been made and will be presented in two MS theses. Mathematical models for the heat exchangers have been evaluated in order to compare the experiments. [D:RE59], [D:RE60].

### 6.3.5 OECD Halden Reactor Project

In Halden a program is running for computer control of the reactor plant. In this work there are two subjects which are of common interest to us. Gustaf Olsson has had contact together with

ASEA-ATOM in the problem of reconstruction of the power distribution in core. Halden has also provided experimental data from the reactor which is presently analyzed by Gustaf Olsson and two MS theses works.

#### 6.3.6 Sydkraft AB

Besides the cooperation on the 160 MW boiler (see section 5.1) two theses have been written [D:RE43],[D:RE56]. Dynamic programming has been used in order to optimize the power distribution from thermal boilers. Even spinning reserve has been accounted for.

#### 6.3.7 Other industries

A MS thesis [D:RE54] has been made for Bolinder-Munktell AB. It handles the problem of controlling the transmission ratio of a hydrostatic transmission of a tractor.

Contact has been taken by Munkfors Bruk AB. Problems on control of furnaces and rolling mills have been discussed. No work has started yet.

With SAAB, Division of Missile Control, we have discussed problem of identification of the time variable dynamics of a missile. The work has not started yet.

At AB Isotopteknik in Stockholm much work have been done by use of radioactive stuff in order to measure all kinds of flows. The radioactive element is inserted at one point and by nuclear measurements the propogation of the flow can be measured. The method has mainly been used to track water pollution in lakes and rivers and flows in paper industry plants. Experimental data have been given by the firm and we are going to identify the dynamics.

In cooperation with Kockums AB experiments are planned on a marine boiler (see section 5.1).

#### 6.4 Trips to industries

During April 1969 a four days trip was made to industries in the middle part of Sweden [F:7]. The trip was possible due to a contribution of the "Universitetskanslersämbetet". Following industries were visited

- SAAB Jönköping and Linköping
- ASEA Västerås
- AGA Stockholm
- Johnsson-Institutet, Nynäshamn

The trip has already resulted in specific projects with three of the firms, SAAB, ASEA and Johnsson-Institute (see section 6.3) and further discussions are planned.



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See also references in Appendices C, D and F.

APPENDIX A - LIST OF PERSONEL

Professor Karl Johan Åström

Univ.lektor Gustaf Olsson

Forskn.ing. Karl Eklund

" Ivar Gustavsson

" Krister Mårtensson

Assistent Johan Wieslander

" Björn Wittenmark

" Per Hagander

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" Sture Lindahl

" Anders Jonson

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APPENDIX B - PUBLISHED PAPERS AND BOOKS

- Report 6804 Åström K.J. "Recursive Formulas for the Evaluation of Certain Complex Integrals", Sept-68. Submitted to Quarterly of Applied Mathematics.
- Report 6805 Åström K.J. "Optimal Control of Markov Processes with Incomplete State Information II - The Convexity of the Lossfunction", Sept-68. Published in JMAA.
- Report 6807 Åström K.J. "On the Choice of Sampling Rates in Parametric Identification of time-series", Nov-68. Accepted for publication in Information Sciences.
- Report 6808 Eklund K. "Numerical Modelbuilding", Nov-68. Published in International Journal of Control.
- Report 6906 Borisson U. and Sogndal C. "Adaptiva reglermetoder", Published in Elteknik 1968, no 9.
- Olsson G. "Processidentifiering: nya metoder att bestämma egenskaper hos reglertekniska system", Teknisk Tidskrift oktober 1968.
- Åström K.J. "Reglerteori", Almqvist & Wiksell, Stockholm 1968.
- Åström K.J. "Introduction to Stochastic Control Theory", to appear.

APPENDIX C - TECHNICAL REPORTS

- (1) Report 6801 Eklund K. "En olinjär matematisk modell för en dompanna", March-68.
- (2) Report 6802 Mårtensson K. "Linear Quadratic Control Package Part I - The Continuous Problem", April-68.
- (3) Report 6803 Gustavsson I. "Parametric Identification of Time Series", April-68.
- (4) Report 6804 Åström K.J. "Recursive Formulas for the Evaluation of Certain Complex Integrals", Sept-68.
- (5) Report 6805 Åström K.J. "Optimal Control of Markov Processes with Incomplete State Information II - The Convexity of the Lossfunction", Sept-68.
- (6) Report 6806 Åström K.J. "Lectures on the Identification Problem - The Least Squares Method", Sept-68.
- (7) Report 6807 Åström K.J. "On the Choice of Sampling Rates in Parametric Identification of Time Series", Nov-68.
- (8) Report 6808 Eklund K. "Numerical Modelbuilding", Nov-68.
- (9) Report 6809 Eklund K. "Linear Mathematical Models of the Drum-Downcomer-Riser Loop of a Drum Boiler", Nov-68.
- (10) Report 6810 Wieslander J. "Reelltidsidentifiering med hjälp av minsta-kvadrat metoden, Försök på pilot-data", Dec-68.
- (11) Report 6901 Eklund K. "Multivariable Control of a Boiler - An Application of Linear Quadratic Control Theory", Jan-69.
- (12) Report 6902 Eklund K. "Multivariable Control of a Boiler", Jan-69.
- (13) Report 6903 Gustavsson I. "Maximum Likelihood Identification of Dynamics of the Ågesta Reactor and Comparison with Results of Spectral Analysis", Febr-69.

- (14) Report 6904 Mårtensson K. "Linear Quadratic Control Package Part II - The Discrete Problem", March-69.
- (15) Report 6905 Åström K.J. "Program för forskningen i regler- teknik vid Tekniska Högskolan i Lund", 24.3.1969.
- (16) Report 6906 Borisson U. and Sogndal C. "Adaptiva regler- metoder".
- (17) Report 6907 Gustavsson I. "Parametric Identification of Multiple Input Single Output Dynamic Sys- tems", July-69.
- (18) Report 6908 Wieslander J. "Real-time Identification - Part I", (to appear).
- (19) Report 6909 Wieslander J. "Real-time Identification - Part II", (to appear).
- (20) Report 6910 Olsson G. "Spatial Xenon Instability in Thermal Reactors", July-69.
- (21) Report 6911 Olsson G. "Digital Simulation of Spatial Xenon Oscillations", July-69.
- (22) Report 6912 Olsson G. "Evaluation of Process Computers", (to appear).
- (23) Report 6913 Klevås J., Leffler N. "Optimering av effekt- fördelning med hänsyn till rullande re- serv för ångkraftaggregat med hjälp av dynamisk programmering", June-69.
- (24) Report 6914 Valis J. "Experimental Comparison of Different Methods for Numerical Identification", June-69.
- (25) Report 6915 Valis J., Gustavsson I. "Some Computational Results obtained by Panuška's Method of Stochastic Approximations for Identifi- cation of Discrete Time Systems", June-69.
- (26) Report 6916 Gustavsson I. "Identification of Dynamics of a Distillation Column", June-69.

Theses in automatic control for the degree of civ.ing., Lund  
Institute of Technology

- RE-1 Häggman, Börje: Dimensionering av ett samplat system med tidsfördröjning (Synthesis of a Sampled System with Time Delay), juni-65.
- RE-2 Svärd, Bo: Undersökning av dynamiska egenskaper hos en industriell process (Investigation of Dynamic Properties of an Industrial Process), mars-66.
- RE-3 Pettersson, Bengt: Optimal reglering av processer med tidsfördröjning (Optimal Control of a Process with Time Delay), juni-66.
- RE-4 Wittenmark, Björn: Adaptiv prediktion (Adaptive Prediction), aug-66.
- RE-5 Mårtensson, Krister: Numeriska algoritmer för lösning av minimaltidsproblemet (Numerical Algorithms for the Solution of the Minimal Time Problem), okt-66.
- RE-6 Ekstrand, Bertil och Larsson, Lars-Erik: Studium av system för temperaturreglering (Analysis of a Temperature Control System), okt-66.
- RE-7 Gustavsson, Ivar: Numerisk lösning av optimala styrningsproblem med Bryson-Kelley metodik (Numerical Solution of Optimal Control Problems using Bryson-Kelley Techniques), nov-66.
- RE-8 Andersson, Erik: Processidentifiering med datamaskin (Numerical Identification of a Process Dynamics using the maximum likelihood method), dec-66.
- RE-9 Eriksson, Kurt-Erik: Numerisk bestämning av processdynamiken (Estimation of Process Dynamics using the least squares method), dec-66.
- RE-10 Herne, Bengt: Experimentella undersökningar av linjära och olinjära reglersystem (Experimental Studies of Linear and Nonlinear Servomechanisms), jan-67.
- RE-11 Horrdin, Sven: Rosenbrocks metod för förenkling av komplicerade system (Simplification of Complex Systems by Rosenbrocks Method), juli-67.

- RE-12 Jönsson, Rolf Lennart: Kulikowskis version av teorin för optimal styrning (Kulikowskis Version of the Theory of Optimal Control), juli-67.
- RE-13 Wallentinsson, Claes: Identifiering av linjär modell för en lättvatten kokareaktor (Identification of a Linear Model of a Light Water Boiling Reactor), aug-67.
- RE-14 Wieslander, Johan: Identifiering av människans överföringsoperator (Identification of a Human Operator), sept-67.
- RE-15 Bååth, Kerstin: Identifiering av olinjära system (Identification of Nonlinear Systems), sept-67.
- RE-16 Eldhagen, Lars-Göran: Datamaskinprogram för analys av regler-system. Transformationer av systemekvationerna (Computer Programs for Linear Analysis. Transformations of the System Equations), sept-67.
- RE-17 Persson, Roland: Optimal kvantisering av styrvariabler i ett reglersystem (Optimal Quantization of the Control Variables in a Linear Quadratic Control Problem), sept-67.
- RE-18 Olofsson, Ingemar: Produktionsplanering på glasbruk (Production Planning at a Glasswork), sept-67.
- RE-19 Mattsson, Bengt: Numerisk lösning av optimala styrproblem med Kenneth-McGills metod (Numerical Solution of Optimal Control Problems using Kenneth-McGills Method), sept-67.
- RE-20 Syding, Rolf: Undersökning av Honeywells adaptiva reglersystem (Analog Simulation of Honeywells Adaptive System), sept-67.
- RE-21 Skoog, Hans: Analys av Margolis Leondes adaptiva reglersystem (Analysis of Margolis-Leondes Adaptive System), okt-67.
- RE-22 Wintzell, Jan-Olof: Identifiering av processdynamik med korrelationsanalys då signalen är en nollsekvens om maximal längd (PRBS) (Process Identification with PRBS signals and Correlation Analysis), okt-67.
- RE-23 Anderberg, Yngve och Hansson, Leif: Reglersystem för kallbandvalsverk (Control of a Strip Mill), nov-67.

- RE-24 Almgren, Per: Konstruktion av elektronikutrustning till enaxlig gyroplattform (Construction of the Electronic Equipment for a single Axis Gyro Platform), dec-6
- RE-25 Andoff, Tommy och Bodin, Bengt: Jämförande analys av data-maskiner för processreglering (Evaluation of Process Control Computers), jan-68.
- RE-26 Sogndal, Roy: Analogisimulering av Honeywells och General Electrics adaptiva system (Analog Simulation of the Honeywells and General Electric Adaptive Systems), april-68. (Publicerad i Elteknik 1968.
- RE-27 Borisson, Ulf: Jämförelse genom analogisimulering mellan manuell styrning och några adaptiva system vid variabel krets förstärkning (A Comparison between Manual Control and Adaptive Regulators for Systems with Time Variable Gain), maj-68. Publicerad i Elteknik 1968.
- RE-28 Ydremark, Anders: Studium av en styralgoritm samt program-system för processdatamaskiner (A Comparison of Program using Systems for Different Process Control Computers), maj-68.
- RE-29 Ryberg, Dick: Projektering och uppbyggnad av liten analogi-maskin (Design and Construction of a Small Analog Computer), juni-68.
- RE-30 Nilsson, Anders: Projektering av apparat för processidentifiering med hjälp av pseudoslumftal (Design of a Correlator for PRBS signals), juni-68.
- RE-31 Johnsson, Gösta och Rosell, Örjan: Identifiering av linjära system med hjälp av impulssvar (Identification of Linear Systems based on Impulse Response Measurements), juni-68.
- RE-32 Langemar, Göran och Lumsden, Kent: Konstruktion av digitalt styrsystem till elektrohydrauliskt servo enligt principen för numeriskt styrda maskiner (Design and test of a Digital Control System for an Electro-hydraulic Servo), juni-68.



- RE-33 Hagander, Per: Minimaltidsproblemet för ett olinjärt system undersökt med dynamisk programmering (Application of Dynamic Programming on the Minimal Time Problem for an Inverted Pendulum), juni-68.
- RE-34 Jonasson, Jan: Dynamiska egenskaper hos en medströms växlare (Dynamics of a Heat Exchanger), aug-68.
- RE-35 Kristensson, Bernt: Detektering av "outliers" (Detection of Outliers), aug-68.
- RE-36 Skarman, Bengt: Experimentell undersökning av processdynamiken hos en indunstare (Experimental Identification of the Dynamics of an Evaporation Plant), aug-68.
- RE-37 Eck, Anders: Experimentell undersökning av temperaturreglering i en värmestav (Experimental Study of a Thermal System), sept-68.
- RE-38 Pålsson, Torsten: Undersökning av optimala system (Examination of Linear Quadratic Optimal Control Systems), okt-68.
- RE-39 Steen, Leif: Programmering av PI-regulator samt olika ställorgan för processdatamaskin (Programming of a PI-regulator for three process computers), okt-68.
- RE-40 Werner, Kjell: Tröghetsdämpade servomotorer (Inertia Damped Servo Motors), nov-68.
- RE-41 Bergman, Jan: Undersökning av Minneapolis-Honeywells adaptiva regulator genom digital simulering (Digital Simulation of Minneapolis-Honeywells Adaptive Controller), nov-68.
- RE-42 Jonson, Anders och Ström, Lars-Magnus: Processidentifiering - Reglerat system samt system med flera in- och utsignaler (Identification of Multivariable and Closed Loop Systems), jan-69.
- RE-43 Lind, Pär: Optimering av effektfördelning mellan ångkraftverk med hjälp av dynamisk programmering (Optimization of power production Distribution using Dynamic Programming), jan-69.

- RE-44 Torlöf, Per: Undersökning av variationer i EEG-spektrum vid olika yttre stimuleringar (A Study of the Variations in EEG-Spectrum at Different External Influences), jan-69.
- RE-45 Andersson, Stig: Analys och kompensering av system med mycket svag dämpning (Experimental Investigation of a Servo with Structural Resonance), jan-69.
- RE-46 Aulin, Börje: Dekomposition av system av hög ordning (Decomposition of Large Systems using Graph Theory), jan-69
- RE-47 Lindén, Per: Tidsvariabla system. Systemekvationerna och deras lösning (Time Variable Systems. Solutions of the System Equations), jan-69.
- RE-48 Lagerlöf, Bengt: En linjär matematisk modell för en dompanna med två överhettare (A Linear Model of a Boiler with Two Superheaters), jan-69.
- RE-49 Hugosson, Lennart: Experimentell utprovning av elektromekaniskt servosystem (Experimental Design of a Electro Mechanical Servo System), jan-69.
- RE-50 Henmark, Christer och Skoog, Tommy: Simulering av njurfunktionen och kroppens cirkulationssystemets långtidsreglering (Simulation of the Human Kidney System and the Long Time Regulation of the Circulating System of the Human Body), jan-69.
- RE-51 Månsson, Lars: Analys av olinjär regulator för servosystem med mättning (Dual Mode Control for a Double Integrator with a Saturated Control Variable), jan-69.
- RE-52 Ljung, Christer och Löwenhielm, Peter: Studium av olika metoder för analys av artefaktfria EEG-signaler (Comparison between different Methods for Analysis of EEG's free from Artefacts), maj-69.
- RE-53 Lundgren, Bertil: Bestämning av överföringsfunktioner med impulssvarsanalys (Determination of Transfer Functions with Impuls Response Analysis), april-69.

- RE-54 Christensson, Nils: Reglering av hydrostatisk transmission i entreprenadmaskiner (Control of the gear change of a Hydrostatic Transmission in an Agricultural Tractor), juni-69.
- RE-55 Larsson, Christer och Öbom, Christer: En matematisk modell av ett ångkraftverk (A Mathematical Model of a Boiler) juni-69.
- RE-56 Klevås, Jan och Leffler, Nils: Optimering av effektfördelning med hänsyn till rullande reserv för ångkraftaggregat med hjälp av dynamisk programmering (Optimization of power distribution for Steam Boilers with respect to Spinning Reserve by Dynamic Programming), juni-69.
- RE-57 Elfving, Thomas och Hultberg, Thomas: Mätning och identifiering av dynamiken på torkpartiet i en pappersmaskin (Measurements and Identification of the Dynamics of the Drying Section of a Paper Machine), Juli-69.
- RE-58 Bengtsson, Gunnar: Förfiltrering av signaler med Kalmanfilter (Optimal Prefiltering with Kalman Theory), juli-69.
- RE-59 Rosengren, Bengt och Nordh, Ingemar: Konstruktion av PRBS-generator (Construction of a PRBS Generator), juli-69