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TRAVEL REPORT FROM USA - JULY 1, 1977 - JULY 3, 1978

BJÖRN WITTENMARK

Department of Automatic Control
Lund Institute of Technology
October 1978

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BJÖRN WITTENMARK

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The travel report describes the research the author did at the University of Connecticut, Storrs, during the academic year 77/78. Several visists to universities and industries were done and some of the impressions from these visists are given.

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1. INTRODUCTION

The visit to the United States was done during the period July 1, 1977-July 3, 1978. The visit was possible to make thanks to support from:

University of Connecticut
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I hereby want to acknowledge these contributions.

The main part of my visit was spent at the Department of Electrical Engineering, University of Connecticut, Storrs, CT. I also visited several other universities and industries and participated in three conferences:

1977 IEEE Conference on Decision and Control, December 7-9, 1977, New Orleans

The Institute of Mathematical Statistics Meeting on Time Series Analysis, May 1-3, 1978, Ames, Iowa

Symposium on Simulation, Modelling and Decision in Energy Systems, June 1-2, 1978, Montreal.

A summary of my research activities is found in Section 2. The impressions from conferences and visits are given in Section 3. A summary is given in Section 4. Lists of seminars, lectures and publications are found in Appendices A and B.

2. RESEARCH ACTIVITIES

My research activities have been concentrated around the following projects:

Identification of human operator models
A two-level estimator for parameter estimation
Dual control
Minimum energy controllers for process control
Model validation

Short descriptions of the projects and some of the obtaind results are given in this section.

Identification of human operator models

An area of main interest at the System Group at UConn is models for human operators. The research in this field is directed by David Kleinman. Together with Gordon Lee and David Kleinman I worked with identification of parameters in the so called "optimal control model" of a human operator. A desription of this model can be found in:

Kleinman D L, Baron S, Levison B: A control theoretic approach to manned-vehicle systems analysis, IEEE Trans Automatic Control, AC-16, No 6, December 1971, 824-832.

The main features of the model is shown in Figure 2.1. The idea behind the optimal control model is that the human operator behaves like an optimal control system. This means that the model consists of a Kalmanfilter, a state predictor and a linear feedback from the estimated state. It is assumed that the human operator has perfect knowledge of the parameters in the process. The parameters in the optimal control model are the covariance matrix of the observation noise, the time delay in the observation, the covariance matrix of the motor noise and the weighting matrices for the quadratic lossfunction used to calculate the optimal state feedback.
A lot of work has been done to model different aspects of the human operator, for instance attention allocation when the operator has to look at several instruments.
The parameters in the model have earlier been selected through "eye-ball" matching. Is has been found that the parameters in the model are quite independent of the controlled system. Also there is a remarkable good fit between the model predictions and experiments.
The work on identification was concentrated on steady state performances,

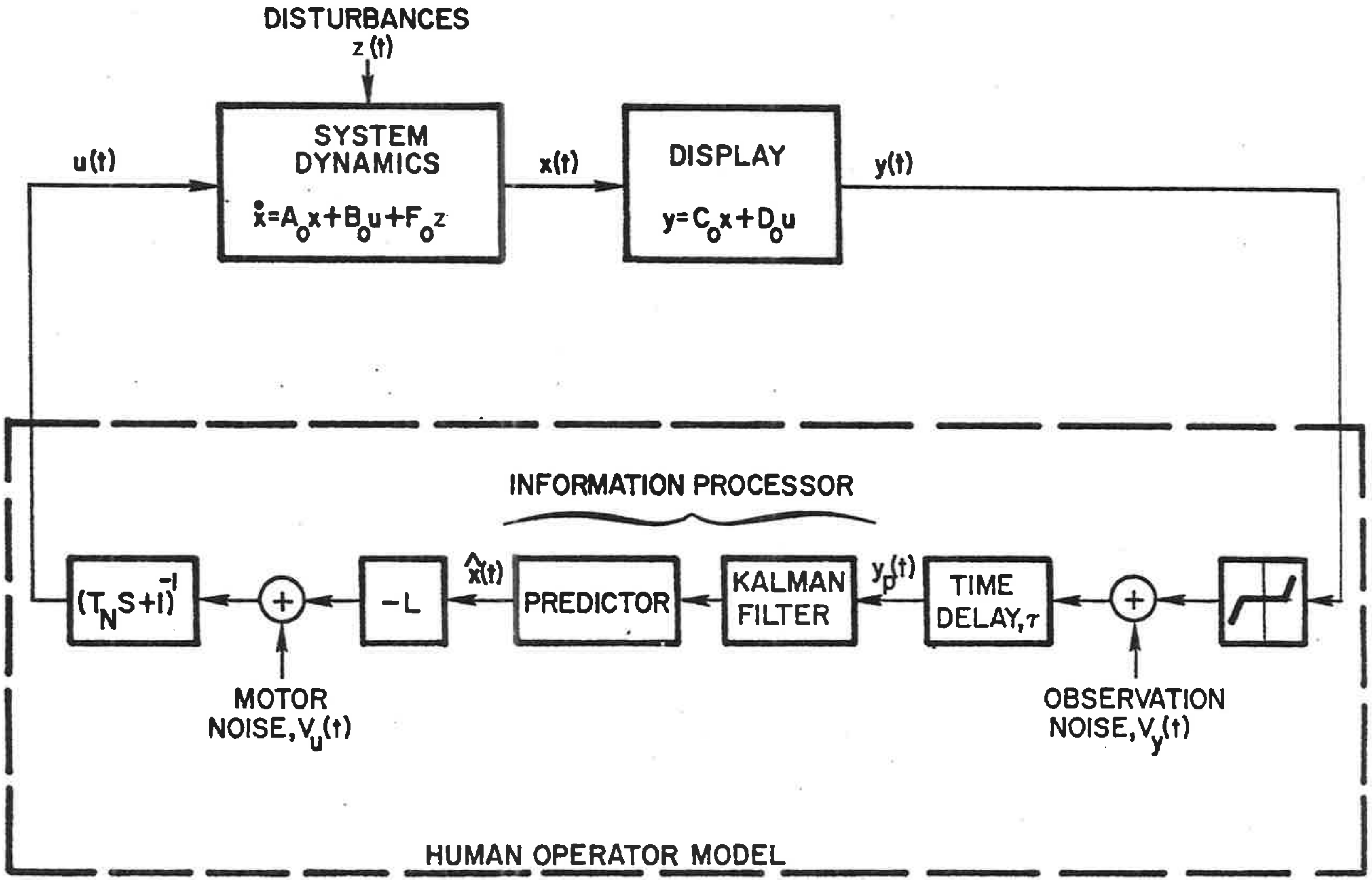

Figure 2.1 The optimal control model for a human operator

i.e. the reference trajectories are constant and the system is only disturbed by noise. The transfer function and the so called remnant are then the standard measurements from an experiment. An identification package was developed consisting of two main subroutines:

STEADY, which produces the basic human operator characteristics (frequency domain values, optimal control gains etc) for given parameters (time delay, measurement and motor noise characteristics)

POWELL, which is a non derivative optimization routine.

The subroutine POWELL was used to find a set of parameters which minimizes a lossfunction. The experimental data were given as:

Magnitude and phase and their standard deviations of the transfer function

The scores (essentially the integrated square of the errors in the different control channels) and their standard deviations

The remnant (essentially everything that is uncorrelated with the control signal) and the standard deviations.

Different types of lossfunctions were used to weight the different data together. The problem is that the data points have different dimensions, and a lot of time was spent on finding relevant ways to make the weighting. The identification package worked well but the computation times are quite long. The subroutine STEADY have to be called every time the optimization subroutine makes a function evaluation. A result of the identification is shown in Figure 2.2 which shows the magnitude and the phase of the model and the experiment. The system is in this case an integrator. There is a very good fit between the model and the experiment except for the low frequency drop in the phase which can not be modelled by the present human operator model. The parameter values obtained from the identification give a lossfunction which is about half of the value obtained by earlier "eye-ball" matching.
The use of identification to find the parameters in the model makes it much easier to test different structures of human operator models by changing the subroutine STEADY. The results were presented at the Annual Manual Conference:

Lee G K, Wittenmark B, Kleinman D L: Identification of parameters in the optimal control model, The 14th Annual Conference on Manual Control, Los Angeles, April 25-27, 1978.

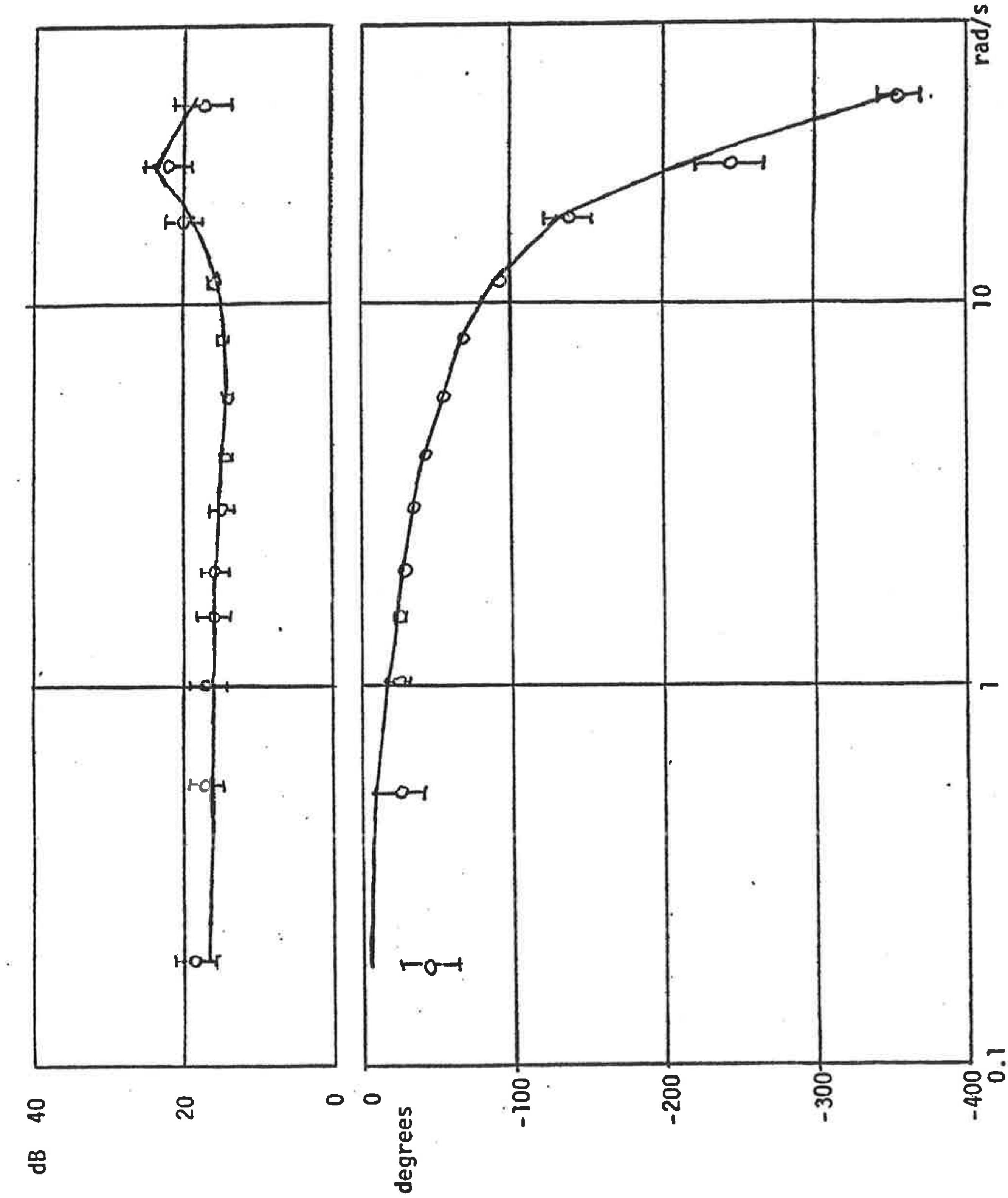

Figure 2.2 The figure shows the measured transfer function and the theoretical transfer function based on the identified parameters. The measured values are shown by rings (o) and the horizontal bar shows the standard deviations. The full line is the transfer function of the model.

A two-level estimator for parameter estimation

The two-level estimator consists of two estimators, a fine and a course estimator. The fine estimator is the usual least squares estimator (Kalman filter) that has good properties if the parameters not are varying too fast. The course estimator consists of a set of fixed apriori models. The fixed model are spread out in the parameter space. The purpose with the course estimator is that it will serve as an information network. It will quickly detect in which area the parameters are for the moment. The two estimators are connected via an information link, which will guide the fine estimator towards the point in the parameter space that is detected by the course estimator. Details of the two-level estimator are given in:

Wittenmark B: A two-level estimator for time-varying parameters, to appear in Automatica, January 1979.

The two-level estimator can be useful in several situations. If the parameters in the process are changing rapidly the fine estimator has problem to follow the parameter changes. This has been seen in connection with research on dual control. The estimation can be improved by introducing the dual effect in the choice of the control signal. With the two-level estimator the parameter estimation is instead improved by introducing the second level of models (the course estimator).
The two-level estimator can also be used to combine adaptation and learning. In an adaptive controller there is no learning feature which takes advantage of that the same type of situation has happend before. The adaptive controller only adapts to the new situation as if it has not seen the same situation before. A learning controller tries to take advantage of earlier experience. The learning feature can now be incorporated in the course estimator. This can be very useful for instance for production changes. When the production is changed it is often advantageous to also change the parameters in the controller. Models of the process at different production levels can then be used in the course estimator. The production rate can then be used as feedforward and to help the course estimator to find the best model. The fine estimator can then quickly find good parameter estimates for the new production level. The fine estimator takes care of the fine adjustment which can be necessary due to other changes in the process. The course estimator only points out the area in the parameter space where the fine estimator most likely can find good parameters.

Dual control

Together with Yaakov Bar-Shalom and Carl Wenk some new ideas in the area of dual control were investigated. The problem with dual controllers is the large numerical calculations. The computations are associated with the estimation of future loss as a function of the present control signal. Different ways are presented in the literature to facilitate the computations. For instance the loss can be computed only a couple of steps ahead. In our work we made some preliminary investigations of other approximations of the future loss.
In our work we assumed that the process belongs to a known finite set of models. The controller then has to choose the most likely model based on the observations. The control signal has to be chosen in order to find the correct model and at the same time the performance of the closed loop system should be satisfactory. In the preliminary analysis it was assumed that the controller should discriminate between only two models. It is possible to extend the results to several models. The calculation of the future loss involves the calculation of the pre posterior densities that the process belongs to one class of the models or the other. In order to estimate the future loss the pre posterior density is approximated by a bimodal distribution. This makes it possible to simplify the computations of the future loss. The control signal is then determined by making a numerical search at each step of time.
Monto Carlo simulations of simple examples show that in many examples it is possible to improve the performance by using an approximate dual controller compared with a controller based on the certainty equivalence principle.

Minimum energy controllers for process control

One of the main concerns of the process industry is to reduce the energy consumption in the processes. The energy consumption can be considerably decreased by using a proper controller. Many operating controllers are, however, not designed from a minimum energy point of view. The control objective has often been to minimize the variation of the output of the process. The set point have then been adjusted to obtain as low energy consumption as possible while still satisfying constraints on the outgoing product. The increasing energy costs have in a sense changed the control objectives. In the project a new design approach was investigated, which explicitely incorporates the minimum energy objective.
It is assumed that the processes are described as known single input single output minimum phase systems. The objective of the control is to meet the

probability constraint

$$\Pr\ (\ y(t) \geq y_{min}\ ) = 1 - \varepsilon$$

The energy consumption was modelled as

$$E\ (u(t)^2) = E(u(t)^2) + Var(u(t))$$

The problem was solved by minimizing the energy consumption and using the quality of the product as a constraint. It is not possible to get an analytic solution to the problem. The control signal must at each step of time be determined via a numerical search procedure. The minimum energy controller is thus more complicated to implement than a conventional controller. Numerical simulations indicate that the performance of the new controller is as good as or better than linear quadratic controllers. The choice of parameters in the controller is easier for the new controller and the computational burden is almost independent of the order of the system. The new controller minimizes a single step ahead loss function. This may cause problems such as it might be necessary to use large control signals at a future step of time.
Further details of the controller can be found in:

Rao P K, Wittenmark B: Suboptimal minimum energy controllers for process control, Symposium on Simulation, Modelling and Decision in Energy Systems, Montreal, June 1-2, 1978.

The connection between single step and multi step lossfunctions is further discussed in:

Wittenmark B, Rao P K: Comments on "Single step versus multistep performance criteria for steady state SISO systems", to appear IEEE Trans Autom Control, AC-24, February 1979.

Model validation

To determine a suitable structure of an identified model is an important problem. Most identification methods are based on a given structure. The user has to test different structures and determine which one fits the data best. Many tests of structure are based on statistical analysis of the prediction errors, for instance the F-test. The results of the tests are at least for real data often inconsistent. The choice of model and model structure should be related to the ultimate use of the model. Most tests for model validation do not say anything about how well the process can be controlled. Further when making structure tests mostly the parameter estimates only are used and not the uncertainties of the estimates. The purpose with this work was to find an approximate way to predict the behavior of the closed loop system without making any additional tests on the process.

In the new test an approximate expression of the expected loss for the closed loop system is calculated. The expected closed loop performance is calculated under the assumption that the parameters are white noise processes with the mean and covariances obtained from the identification routine. In the white parameter case it is assumed that the parameters at each step of time is drawn from a given distribution. The calculated loss and the effect of the uncertainties are calculated for different model structures. The underlaying idea is that one should choose a model structure which gives a desired behavior and which also is as insensitive as possible to errors in the parameters. The new method is so far only tested on simulated data. The advantages of the test are:

- It takes parameter uncertainties into account
- It calculates an approximate expected loss of the closed loop performance
- Time consuming on-line tests or Monte Carlo simulations are avoided.

Further details can be found in:

Wittenmark B, Bar-Shalom Y: Model validation from estimated closed loop performance, Submitted to the 5th IFAC Symposium on Identification and System Parameter Estimation, Darmstadt, September, 1979.

3. SEMINARS, LECTURES AND VISITS

A list of seminars and lectures that I held is found in Appendix A. During the fall 1977 I had a graduate course in Identification of dynamic systems at the University of Connecticut. The course was on 42 hours and contained lectures, exercises and a test case. Graduate students from the university as well as people from the industry participated in the course.

Honeywell Inc., Minneapolis, October 11-12, 1977

I visited the Systems and Research Center and had discussions with Rhall Pope, Günter Stein, Charlie Harvey and Jim Hauge. There was a great interest in applications of self-tuning regulators on several types of processes.
The Systems and Research Center are making fundamental research and applications as a contractor for the defence, NASA and other divisions of Honeywell.

University of Massachusetts, Amherst, October 18, 1977

I had discussions mainly with Dick Monopoli. We discussed adaptive control and education in automatic control.
Earlier they have mainly been working with continuous time systems, but recently they have looked how the same type of ideas can be used for sampled data systems.
I also discussed education. The fall 1977 was the first time that they in the introductory course in control treated continuous and discrete time systems in the same course. According to their experience there was no problems for the students to learn about the two types of systems in parallel. The used the book: Sancedo, Schiring: Introduction to continuous and digital control systems, MacMillan 1968. The book is not perfect to use since there is really no interaction between the continuous and digital parts of the book.

Honeywell Inc., Fort Washington, December 5, 1977

The process control division of Honeywell is in Fort Washington, just outside Philadelphia. Among other things that they are producing at Fort Washington is the TDC 2000 system. This is a hierarcal system for process control based on micro and minicomputers. The lowest level is the decentralized microprocessors which controls one or several local loops, mainly using different versions of PID-controllers. The parameters of the controllers as well as set points can be changed from the higher level computers. The TCD 2000 system has been a great success and at Honeywell one believe that this is a good way to build decentralized process control systems.

Conference on Decision and Control, New Orleans, December 7-9, 1977

The CDC conference was held in New Orleans and I had many possibilities to discuss with people from all over the US and also from Europe. The quality of the conference was much better then the at an average conference and people were openminded and willing to discuss their research. I was vice chairman at the session an Adaptive Control Systems.
The conference proceedings are available at the department in Lund.

Case Western Reserve University, Cleveland, January 17, 1978

I visited the Department of Systems Engineering and Information Sciences. Steve Kahne is the head of the department and we discussed among other things a student exchange program between Case and universities in Sweden. We also discussed the possibilities to organize a workshop on self-tuning regulators.
The exchange program has been set up between Case and Uppsala. The intension is that undergraduate students will get the possibility to take courses at Case. One estimates that 10-20 students will go to Case every year.
Prof Irving Lefkowitz described the research program at Case. Apart from usual sources for grants as NSF they have an industrial sponsor group . The sponsor group has been working since 1954 and there is now eight industries in the group . The fonds are freely used by the department to support graduate students in different feasibility studies. The areas are determined by the department.
The laboratory facilities for control were limited and included some of the most common experiments as level control etc.
The department is now in progress of buying a hierachal computer system from Foxboro. The new system will have the facility to make it easy to connect different physical processes to the computer and to make communication between different computers.

3M Company, St Paul, January 18, 1978

I met Kris Burhardt and Assad Alam. Burhardt is responsible for the control group which solves control and measurement problems for other sections of the company. For the moment one is interested in self-tuning regulators and have made an installation on a LSI-11. The computer is going to be used on different processes to test the feasibility of self-tuning regulators. Some preliminary experiments on real processes and pilot plants have been done and they have found that the basic self-tuning regulator has a good performance.
When simulating a process on an analog computer they have noticed bursts. The problem occured when the noise level was very low and when there was an

exponential decay of old information. We discussed different ways to avoid the problem. The had avoided the problem by introducing a "knowledge factor", which is defined as the norm of the gain in the Kalman filter. When the knowledge factor is small they stop the updating of the parameters and the P-matrix.

University of Minnesota, Minneapolis, January 19, 1978

I discussed with Fred Bailey, Bruce Lee, Pat Kumar and George Stefanopolis. The seminar I held was transmitted via cable to six different industries in the neighborhood of Minneapolis. Seminars and some regular courses are transmitted over the network.

For the undergraduate courses they had a computer aided design package implemented on a PDP-8. The students can compute Bode diagrams, root locus, power spectrum. The program package is used in several different courses for instance control, aucustics and filter design.

They used analog computers and an electrical servo system similar to the systems used in Lund for the introductory course in control. The servo is also used to make digital control and the students investigate the influence of the different parameters in a digital PID-controller.

I also discussed decentralized control with Bailey. He pointed out that it is difficult to formulate a good decentralized problem if one does not include some cost for information exchange.

Rensselaer Polytechnic Institute, Troy, February 23, 1978

I met and discussed with Howard Kaufman, Bob Redinbo and Mike Wozny. Kaufman is working on a model reference type of adaptive systems, continuous time systems without noise, where one wants perfect model following. The type of solution is similar to Landau´s but the conditions are simpler. Redinbo is in computer science and they have designed an array processor, which makes it possible to considerably speed up the computations for instance when making FFT.

Wozny is in charge of the computing facilities. They have a dual Prime system with 4 terminal (will shortly be extended to 36 terminals). They have programs for classical design which the students can use during the course work.

Wozny was last year at NSF where he was in charge of the grants in the area of control and operational research. The total amount for the grants was $3M per year. 25% was for OR and the rest for dynamical systems research. One main area was large systems. There were smaller activities in adaptive control but he regarded that as a very promising area.

Institute of Mathematical Statistics Meeting, Ames, May 1-3, 1978

The IMS meeting was on Time Series Analysis and I was invited to have a lecture on self-tuning prediction and smoothing. After the lecture I had several interesting discussions with people about the sel-tuning idea.

McGill University, Montreal, May 31, 1978

I discussed mainly with Pierre Belangêr about self-tuning regulators. They have good experience of simulations and applications. They have used a self-tuning regulator to control a titanium dioxide kiln. By using a self-tuning regulator it was possible to increase the percent of time for the product to be withing the specifications from 64% to 85%. Also it was found that the self-tuning regulator decreased the transtion times at grade changes. The time for a grade change have at some occations been decreased from 10-12 hours to 2 hours. Due to limitations in available memory space in the online computer it was necessary to use a small number of parameters. This was made possible by using as the process the closed loop combination of the kiln and a fixed regulator.

Symposium on Simulation Modelling and Decision in Energy Systems, Montreal, June 1-2, 1978

This was a conference with about half of the participants from the universities and half from the industry. I had two papers at the conference. One on minimum energy controllers, see Section 2. The other paper was:

> Hamza M H, Sheirah M A, Wittenmark B: Prediction of natural gas disposition.

This paper is based on investigations I did in Calgary 1974 concerning prediction of gas consumption in a gas network in Alberta, Canada. The self-tuning predictor has been used to make one-month-ahead predictions using monthly data from six years. It was found that the self-tuning predictor makes a good prediction and can adapt to the increasing amplitude in the yearly oscillations.

Yale University, New Haven, June 29, 1978

I had a long interesting discussion with Steve Morse, who is very interested in the connections between model reference adaptive controllers and self-tuning regulators. He has been working on finding conditions when continuous model reference adaptive controllers are globally stable. He has derived a set of equations which incorporates the essential problems and they are now analyzing the equations in order to find new conditions for stability.

University of Connecticut, Storrs

The department I vistied consists of two subdepartments: Electrical Engineering and Computer Science. In the Electrical Engineering department there is a large interest in control systems. An informal Systems Group consists of David Kleinman, Yaakov Bar-Shalom, Charlie Knapp and Dave Jordan.

David Kleinman is mainly working in the area of human operator models, see Section 2. Two MS students, two PhD students and one postdoctorat fellow were also working in this field. The current interest in the human operator modelling were for instance the influence of acceleration stress and attention allocation.

Yaakov Bar-Shalom is working in the field of adaptive and stochastic control. This type of control has been used on econometric models.

Charlie Knapp is working with Kalman filters and estimation. Dave Jordan has done work in design of sampled data systems using pole-placement technique.

The facilities in the control laboratory is very limited. Late during my visit they got a PDP 11/60 system, which is going to be used for the research on human operator models, both for batch computations and for experiments. They are also going to install a centrifuge, which can be used to simulate acceleration sress.

For analysis and synthesis of control systems they have a good program library, mainly developed by David Kleinman. The library contains subroutines for matrix and polynomial calculations for computing linear quadratic controllers.

At the department there was a good serie of seminars by people travelling through Storrs. Also every week there was an internal seminar held by the staff and the students.

The students and the staff at the university have easy access to computers. The Computer Center had many terminals at the Center and at different locations at the campus. Most programs were run from terminals. This made it easy to use the computer at all levels of the education.

4. SUMMARY

My visit to USA was a very good experience and gave me many possibilities to discuss with people in my field of interest. This interaction has been very stimulating and have given many new ideas.
It is very difficult to summarize the impressions since I visited so many different kind of places. Some final remarks can, however, be of interest:

- o Most universities have more computer time available than we are used to in Lund. Also there are more terminals available at different locations at the campuses. There are, however, very few places where they have made a large effort to build up good program libraries in the control field.

- o There were very few control laboratories at the places I visited. Most laborations were done using computer simulations.

- o Most people were uncertain in which direction the control field is (should be) moving. Many talked about decentralized control and large scale systems. Also the feeling was that in the next coming years one will see many more applications of advanced control of industrial processes.

APPENDIX A
LIST OF SEMINARS AND LECTURES

1977

Fall 1977	Identification of dynamic systems (14 lectures, 42 hours) UConn
September 20	Design of digital controllers, UConn
October 12	Self-tuning algorithms for control, prediction and smoothing, Honeywell, Minneapolis
October 18	Self-tuning algorithms for control, prediction and smoothing, University of Massachusetts, Amherst

1978

January 17	Self-tuning algorithms for control, prediction and smoothing, Case Western Reserve University, Cleveland
January 19	Self-tuning algorithms for control, prediction and smoothing, University of Minnesota, Minneapolis
February 14	Introduction to self-tuning regulators, UConn
February 21	Self-tuning regulators - The algorithm, UConn
February 23	Self-tuning algorithms for control, prediction and smoothing, Rensselaer Polytechnic Institute, Troy
February 28	Self-tuning regulators - The properties of the algorithm, UConn
March 7	Self-tuning regulators - Pole placement algorithms, UConn
April 4	Self-tuning algorithms for prediction and smoothing, UConn
April 11	Industrial applications of self-tuning regulators, UConn
May 2	Self-tuning algorithms for control, prediction and smoothing, Invited presentation at the Institute of Mathematical Statistics Meeting on Time Series Analysis, Iowa State University, Ames
May 8	Adaptive control - Industrial tool or academic toy, UConn
May 31	Self-tuning algorithms for control, prediction and smoothing, McGill University, Montreal
June 2	Suboptimal minimum energy controllers for process control, Symposium on Simulation, Modelling and Decision in Energy Systems, Montreal
June 29	Self-tuning algorithms for control, prediction and smoothing, Yale University, New Haven

APPENDIX B
LIST OF PUBLICATIONS

Wittenmark B, Rao P K: Comments on "Single step versus multistep performance criteria for steady state SISO systems", Accepted for publication in IEEE Trans on Automatic Control, February 1979

Wittenmark B: A two-level estimator for time-varying parameters, Accepted for publication in Automatica, January 1979

Lee G K, Wittenmark B, Kleinman D L: Identification of parameters in the optimal control model, The 14th Annual Conference on Manual Control, Los Angeles, April 25-27, 1978

Rao P K, Wittenmark B: Suboptimal minimum energy controllers for process control, Symposium on Simulation, Modelling and Decision in Energy Systems, Montreal, June 1-2, 1978

Hamza M H, Sheirah M A, Wittenmark B: Prediction of natural gas disposition, Symposium on Simulation, Modelling and Decision in Energy Systems, Montreal, June 1-2, 1978

Wittenmark B: Self-tuning algorithms for control, prediction and smoothing, Invited paper at the Institute of Mathematical Statistics Meeting on Time Series Analysis, Ames, May 1-3, 1978

Wittenmark B, Bar-Shalom Y: Model validation from estimated closed loop performance, Submitted to the 5th IFAC Symposium on Identification and System Parameter Estimation, Darmstadt, September, 1979

Åström K J, Westerberg B, Wittenmark B: Self-tuning controllers based on pole-placement design, Department of Automatic Control, Lund Institute of Technology, LUTFD2/(TFRT-3148)/1-052/(1978), May 1978