LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT 1992/93

Contents

Chapter 1

Introduction

The Division of Automatic Control at Linköping University consists of some twenty-five people. We teach thirteen undergraduate courses to more than eleven hundred students. The courses cover both traditional control topics and more recent topics in model building and signal processing.

Our research interests are focused on the following areas:

- *Nonlinear Modelling and Control*: Here we are interested both in developing theory for nonlinear systems and to understand and utilize how modern computer algebraic tools can be used for practical analysis and design.

- *System Identification and Signal Processing*: We are interested in a number of aspects ranging from applications of modern signal processing techniques in automobiles, to theoretical aspects in how to evaluate model quality in the presence of under-modelling.

- *Hybrid modelling*: This is an important and emerging field covering problems of how to deal with systems with both discrete and continuous phenomena. The modelling of discrete event dynamic systems (DEDS), sequential planning control problems, and various supervision problems also belong to this area.

We thank The Swedish Board for Technical Development (NUTEK) and the Swedish technical Research Council (TFR) for funding a major part of our research.

A main event during the year has been that our research associate, Dr Mats Viberg, has been appointed Professor of Signal Processing at Chalmers Institute of Technology.

We have also graduated 4 new Ph.Ds during the year: Tommy Svensson, Sören Andersson, Håkan Hjalmarsson and Inger Klein. Moreover, Jonas Sjöberg received his Tekn.Lic. Degree.

In the following pages the main research results obtained during the academic year 1992/93 are summarized. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge. We also offer a service where anyone interested can have direct access to them using ftp or the mailserver. The procedure for this is described below in Section 2.

Russian-Swedish Meeting on Automatic Control

In September 1992 we organized a First Russian-Swedish Meeting on Automatic Control in Linköping. This is part of an effort to link the researchers in the former Eastern block closer to the Western research. The following researchers from Russia and Sweden participated in our meeting:

- A. E. Barabanov, St Petersburg University, St Petersburg, Russia
- T. Bohlin, Royal Institute of Technology, Stockholm, Sweden
- V. N. Bukov, Institute of Control Sciences, Moscow, Russia
- B. Egardt, Chalmers Institute of Technology, Gothenburg, Sweden
- M. Fabian, Chalmers Institute of Technology, Gothenburg, Sweden
- E. A. Fedosov, Institute of Control Sciences, Moscow, Russia

- A. L. Fradkov, Academy of Sciences of Russia, St Petersburg, Russia
- S. V. Gusev, St Petersburg University, St Petersburg, Russia
- P. Hagander, Lund Institute of Technology, Lund, Sweden
- T. Hägglund, Lund Institute of Technology, Lund, Sweden
- V. B. Kolmanovsky, MIEM, Dept. of Cybernetics, Moscow, Russia
- B. Lennartsson, Chalmers Institute of Technology, Gothenburg, Sweden
- V. A. Lototsky, Institute of Control Sciences, Moscow, Russia
- L. Ljung, Linköping University, Linköping, Sweden
- A. Malmgren, Uppsala University, Uppsala, Sweden
- M. Millnert, Linköping University, Linköping, Sweden
- A. V. Nazin, Institute of Control Sciences, Moscow, Russia
- K. Nordström, Uppsala University, Uppsala, Sweden
- A. A. Pervozvanski, St. Petersburg, Russia
- A. S. Poznyak, Institsute of Control Sciences, Moscow, Russia
- S. L. Shishkin, Academy of Sciences, St. Petersburg, Russia
- T. Söderström, Uppsala University, Uppsala, Sweden
- B. Wahlberg, Royal Institute of Technology, Stockholm, Sweden
- V. A. Yakubovich, St Petersburg University, St Petersburg, Russia

Chapter 2

Network Services

There are a number of ways you can access the work produced at this group. The most useful is probably electronic mail to the person you wish to get in contact with. The email addresses are listed at the end of this activity report. Apart from these, shorter but quite arbitrary email addresses you can always use the general form: `FirstName.LastName@isy.liu.se`, e.g. `Lennart.Ljung@isy.liu.se`.

We also have a generic email address:

`Automatic.Control@isy.liu.se`

or `AC@isy.liu.se` for short. Emails sent to this address are currently sent to our secretaries Ingegerd and Ulla.

Finally you can also retrieve reports and software electronically. This is our preferred method of distributing reports.

2.1 Mail Server

You can request a report through electronic mail. Some of the advantages of using electronic mail is that networks with less than full Internet connection can still have access to this repository. Also you do not have to stay connected while you retrieve material.

This means you are less sensitive to the delays offered on some heavily used parts of Internet. We currently only support report distribution through the mail server.

Basic Use

To use the mail server send email to

```
ACMailServer@isy.liu.se
```

and in the body of the email have a message of the form:

```
send <document>
```

You will then first receive an email that is a log of whether or not the mail server was able to process your request. This log will also hold information such as the size of the requested item as well as the encoding and packaging used. If the processing was successful you will receive a sequence of mails containing the requested items. When you have received the requested items you need to reassemble the pieces if it was split into several pieces as well as decode concatenated file.

In order to find what items are available there are a number of indices. The basic index files currently available are:

```
ReportIndex    CompleteReportIndex
ReportIndex93  CompleteReportIndex93
ReportIndex92  CompleteReportIndex92
ReportIndex91  CompleteReportIndex91
```

where `ReportIndex`*year* is a list of reports directly available in that year. `ReportIndex` is the concatenated version of yearly indices. The files `CompleteReportIndex` work analogously to the `ReportIndex` files, but these are complete records of what has been produced in this group. If you need a report that currently is not available you can either contact the author through email or send your request to the generic email address `AC@isy.liu.se` as described above.

Getting Help

There are a number of help files available. They can be activated using the following messages in the body of your email:

help This will give you a basic listing of the available commands, much like the help you get from an ftp server.

send help This will give you a comprehensive help file on how this mail server works.

send AChelp This will give you some basic help about available material in the Automatic Control repository.

Packing, Coding and Compression

Unfortunately the email standards have not quite kept pace with the growth in sizes and varied contents of email traffic. One effect of this is that you will have to *manually* deal with a number of issues normally handled by a decent protocol. These are:

Packaging: There is a limit to the size of emails that can be carried by Internet. This forces us to split documents over several emails. The default size used by our server is $64KB$, but you may change this, see help files for more info:

Coding: We store all our documents in compressed PostScript format. Since this is a binary file we need to encode this in ASCII[1] somehow. We use `uuencode` for the coding and `uudecode` for decoding. If you have access to a Unix based system you are likely to have this available. As a service to DOS users we provide a version of `uudecode` called `uudo`. This program actually also deals with the unpacking part and you can find it under `/pub/Software/DOS` through anonymous ftp, see below.

Compression: We currently use PostScript as the storage format for documents. Since PostScript tends to be rather verbose, compression ratios can be on the order of 4-5. We use two compression schemes. For Unix users we use `compress` which yield files with suffix `Z`. For DOS users we use `zip` which yield files with suffix `zip`. The corresponding decompression programs are called `uncompress` and `unzip` respectively.

2.2 Anonymous FTP

We also have an anonymous ftp server. If you have access to a windows based ftp program such as `ftptool` this is a very nice way of having direct access to reports and software. The basic address is:

```
joakim.isy.liu.se (130.236.24.1)
```

The basic file structure is:

```
/pub:
Reports Software Misc
```

[1]The basic email standard used on Internet SMTP currently assumes everything to be ASCII, which means that the eighth bit may be changed as a message is transmitted.

Below this point it is self instructing. Don't forget to use the binary transfer mode when you get compressed files.

2.3 Future Services

We look forward to your feedback (:-)) regarding these services. We would also like get to suggestions for future services. One possible service is to offer a subscription service to reports, *i.e.*, you would receive an email whenever a document is produced within your domain of interest. Another possibility would be to set up a local gopher node, This could then form a part of a larger structure in the control community.

Chapter 3

A Retrospective

Where did our Ph.Ds go?

Since 1982, the Division of Automatic Control has graduated 18 doctors of technology. As a retrospective view in this year's annual report, we will review the list of our doctors, and what they are doing today.

Mille Millnert, June 2, 1982:
Identification and Control of Systems Subject to Abrupt Changes.
Opponent: Professor Alan Willsky, MIT.
Mille Millnert is now lecturer at our department. He is also chairman of the board for the study programme of Applied Physics and Electrical Engineering and an Associate Chairman of the Department of Electrical Engineering.

A. J. M. van Overbeek, November 26, 1982:
On-line Structure Selection for the Identification Multi-Variable Systems.
Opponent: Professor Keith Glover, Cambridge.
Ton van Overbeek now works for the European Space Agency in Noordwijk, The Netherlands.

Bengt Bengtsson, December 16, 1982:
On Some Control Problems for Queues.
Opponent: Professor Adrian Segall, Technion, Israel.

Bengt Bengtsson is now with the company Sectra AB in Linköping, where he works with consulting in control and equipment for climate control.

Stefan Ljung, April 22, 1983:
Fast Algorithms for Integral Equations and Least Squares Identification Problems.
Opponent: Professor Albert Benveniste, INRIA, Rennes, France.
Stefan Ljung now works for the SAAB Military Aircraft Company with problems related to EMP properties of aircraft.

Henrik Jonson, December 21, 1983:
A Newton Method for Solving Non-linear Optimal Control Problems with General Constraints.
Opponent: Professor Birger Qvarnström, Chalmers Institute of Technology, Gothenburg, Sweden.
Henrik Jonson now works with the SAAB Missile AB in Linköping with various questions related to missile guidance.

Eva Trulsson, January 20, 1984:
Adaptive Control Based on Explicit Criterion Minimization.
Opponent: Professor Karl Johan Åström, Lund Institute of Technology, Lund, Sweden.
Eva Trulsson also works with the SAAB Missile Company in Linköping with questions around communications, command and control.

Kjell Nordström, May 22, 1987:
Uncertainty Robustness and Sensitivity Reduction in the Design of Single Input Control Systems.
Opponent: Professor Bo Egardt (then) ABB Automation, Västerås, Sweden.
Kjell Nordström is now a lecturer at the Controls and Systems Analysis group at Uppsala University in Sweden.

Bo Wahlberg, June 5, 1987:
On the Identification and Approximation of Linear Systems.
Opponent: Professor Michel Gevers, Universite Louvain-la-Neuve, Belgium.
Bo Wahlberg is now Professor of Automatic Control at the Royal Institute of Technology in Stockholm, Sweden.

Svante Gunnarsson, September 23, 1988:
Frequency Domain Aspects of Modelling and Control in Adaptive Systems.

Opponent: Professor Torsten Söderström, Uppsala University, Sweden.
Svante Gunnarsson is now a lecturer in our department.

Alf Isaksson, September 29, 1988:
On System Identification in One and Two dimensions with Signal Processing Applications.
Opponent: Professor Ben Friedlander, University of California at Davis, USA.
Alf Isaksson is now a lecturer in Automatic Control at the Royal Institute of Technology in Stockholm, Sweden.

Mats Viberg, October 13, 1989:
Subspace Fitting Concepts in Sensor Array Processing.
Opponent: Professor Mos Kaveh, University of Minnesota, Minneapolis, USA.
Mats Viberg is now Professor of Signal Processing at Chalmers Institute of Technology, Gothenburg Sweden.

Krister Forsman, December 18, 1991:
Constructive Commutative Algebra in Non-linear Control Theory.
Opponent: Professor Michiel Hazewinkel, Mathematical Centre, Amsterdam, The Netherlands.
Krister Forsman is now a research associate in our department.

Fredrik Gustafsson, April 15 1992:
Estimation of Discrete Parameters in Linear Systems.
Opponent: Professor Michele Basseville, INRIA, Rennes, France.
Fredrik Gustafsson is now a research associate in our department.

Peter Nagy, June 5, 1992:
Tools for Knowledge-based Signal Processing with Applications to System Identification.
Opponent: Docent Holger Broman, Chalmers Institute of Technology, Gothenburg, Sweden.
Peter Nagy is now a researcher in the National Defense Research Laboratory in Linköping, Sweden, working with various signal processing problems.

Tommy Svensson, September 25, 1992:
Mathematical Tools and Software for Analysis and Design of Non-linear Control Systems.

Opponent: Professor Derek Atherton, University of Sussex, Brighton, United Kingdom.
Tommy Svensson now works with the Bofors Underwater Systems, Motala, Sweden, with various problems regarding control and guidance of torpedoes.

Sören Andersson, December 7, 1992:
On Dimension Reduction in Sensor Array Signal Processing.
Opponent: Professor Johann F. Böhme, Ruhr Universität, Bochum, Germany.
Sören Andersson currently has a post doc position at Yale University working with Professor Arye Nehorai.

Håkan Hjalmarsson, April 2, 1993:
Aspects on Incomplete Modelling in System Identification.
Opponent: Dr Robert Kosut, Integrated Systems Inc., Santa Clara, USA.
Håkan Hjalmarsson is now a research associate in our department.

Inger Klein, April 30, 1993:
Automatic Synthesis of Sequential Control Schemes.
Opponent: Professor Peter Caines, McGill University, Montreal, Canada.
Inger Klein is now a research associate in our department.

As a special case we should add Björn Ottersten who defended his thesis: *Parametric Subspace Fitting Methods for Array Signal Processing*, at Stanford University, USA, with Tom Kailath as supervisor. He and Mats Viberg worked together on related projects and shared their time between Stanford and Linköping. Björn Ottersten is now Professor of Signal Processing at the Royal Institute of Technology in Stockholm, Sweden.

Chapter 4

System Identification and Adaptive Control

The research in system identification has covered a fairly wide range of problems. In the sections below the subareas will be covered. Some general expositions of the system identification problem are given in [11] and [12], as well as in [41] and [55]. A view on neural networks was presented in [42] and software issues are discussed in [15]. Radial basis wavelet networks are studied in [91] and the use of bond-graphs in system identification is discussed in [34].

The use of differential algebraic tools, as presented in earlier annual reports is further described in [20] and [46], where implications for robust identifiability also are drawn.

Tracking problems are considered in [19] and [39], as well as in [11] and [35].

4.1 Fully Parameterized State-Space Model Structures

When identifying multivariable systems, *i.e.*, systems with several inputs and outputs, the question of parameterization is always difficult. If we are interested in identifiable parameterizations, *i.e.*, parameterizations which yield unique parameter values when the number of data tends to infinity, we encounter problems. There exists no single identifiable parameterization which can describe all systems of a given order. A standard solution is to estimate models from the data using different identifiable parameterizations and pick the best one.

A new approach is to overparameterize the model to obtain one model structure which includes all systems of a given order. In [104] we propose a model structure which parameterize all the matrices in the state-space model. In order to make the optimization problem well conditioned we introduce a regularized prediction error criterion. This model structure is clearly not identifiable but we show that the statistical quality of the estimated predictor coincides with a standard identifiable model. A new degree of freedom is also introduced since we can choose any form of realization we desire. This freedom is utilized in an identification algorithm to obtain a balanced realization. The choice of realization is based on the good numerical properties of the balanced realization.

4.2 Model Quality

A model is useless without an estimate of its reliability. Any modeling, estimation or identification procedure must therefore be accompanied by a method to assess the accuracy of the delivered model. One could even say that the product delivered to the user must be a set of models, among which a useful or "true" description is (likely) to be found. If the objective is to design a regulator, it is actually the delivered set that is the input to the (robust) control synthesis.

One part of the modelling error is the variability error or random error – when we repeat an experiment with the same input we get a different output. It is common to model these disturbances as random variables. In [8] one way to estimate the random error in parametric estimates is developed. A different, and more direct, method is given in [56]. A thorough treatment of these methods can be found in [3].

It is also possible to attribute this variability in the output to the system itself. It may in some sense be ill-defined and hence respond differently at different times. Means to model, detect and estimate such variability are examined in [44], [57] and [3].

4.3 The Role of Disturbances

Based on a different approach, [7] describes a method to deal with unmodelled dynamics.

An important aspect of system identification is that of robustness — an estimator should be insensitive to the behavior of external disturbances and simultaneously maintain good accuracy. Recently, the approach where so called unknown-but-bounded disturbances are assumed has received a renewed interest. This assumption leads to algorithms that are fundamentally different from those that are suitable when "standard" stochastic noise is assumed. An illustration of this is given in [18] where it is shown that the least-squares estimate diverges if the model order is allowed to increase without bounds.

However, if the additional assumption is made that the "source" that generates the noise is not allowed to see the input signal, *i.e.* the input and the disturbance are uncorrelated, then the same properties as in the stochastic case can be recovered by using an input signal that is a realization of a stochastic process [3].

4.4 Model Validation

In model validation it is a well-known fact that the asymptotic variance of statistics such as

$$\frac{1}{\sqrt{N}}\sum_{t=1}^{N}\varepsilon(t,\hat{\theta}_N)u(t-\tau)$$

may differ from the asymptotic variance of

$$\frac{1}{\sqrt{N}}\sum_{t=1}^{N}\varepsilon(t,\theta^*)u(t-\tau)$$

even if $\hat{\theta}_N \to \theta^*$. This implies that the true level of significance (or equally the power) of the test may be very different from the designed one. This problem is examined in [3] where it is shown that it is possible to construct the statistics in such a way that this problem is avoided.

4.5 Artificial Neural Network as a Black-Box Structure

There has been a growing interest in artificial neural networks (NN) in various applications during the past years. Many results, well-known in statistics or other scientific fields, have been rediscovered in the NN context. In our project we analyse NN in a system identification perspective, viewing NN as "just another model set". An overview of this viewpoint can be found in [42] and in [5] convergence, consistency, and identifiability results can be found.

A characteristic feature of NN models is that the number of parameters is quite high which should raise worries, since it is bound to give a large "variance error". Nevertheless NN's have shown good abilities for modelling different nonlinear systems. This is due to regularization which can be described as

$$W_N(\theta) = V_N(\theta) + \delta \mid \theta - \theta_{\#} \mid^2 \tag{4.1}$$

being minimized instead of $V_N(\theta)$, which is the usual sum of squared errors.

Figure 4.1: Solid line: no regularization; dashed line: regularized with 10^{-2}.

In [5] and in [33] it is shown how the regularization improves the variance error. Further it is shown that in case no explicit regularization is used but the iterative search is terminated before the true minimum is reached, then this also corresponds to a regularization, implicitly. In Figure 4.1 this is shown. A NN is used to model a dynamical system and $V_N(\theta)$ is computed for the validation data after every iteration of the minimization procedure. When the criterion was $W_N(\theta)$, with an appropriate choice of δ, we obtained the dashed line, and in case $V_N(\theta)$ was minimized we ended up with the solid line. In this case we clearly see how the fit becomes worse after a certain number of iterations which corresponds to a regularization which is gradually switched off.

Thanks to the regularization some parameters (or directions in the parameter space) are excluded from the fit. These parameters do not have to be preselected but, the decision is so to speak taken by the data itself.

4.6 Adaptive Control

Within the adaptive control area the work has been concentrated to an application carried out together with the Department of Mechanical Engineering. The application consists of a flexible mechanical structure (lorry crane) controlled by hydraulic actuators. The aim is to design an adaptive control system that reduces the oscillatory behavior of the crane. Applying LQG design to a linearized model gives information concerning a suitable regulator structure. The tuning of the parameters in the regulator is carried out using on-line identification of the system dynamics. Results are presented in [32] and [48] with emphasis on the LQG design and the on-line identification respectively.

4.7 Bounded Disturbances

Identification of systems subject to bounded noise using the recursive least squares method has been considered for a particular choice of design variables. In [14] some asymptotic error bounds are derived using ideas from bounding ellipsoid algorithms. The bounds show the influence of the noise distribution and the input signal character on the model error.

4.8 Time-Frequency Resolution Using Parametric Techniques

It is a basic problem in many applications to study and track the time-varying properties of various signals. This is at the heart of adaptation and detection mechanisms, and there is a rich literature on this subject.

In many contexts it is very attractive to describe the signal characteristics in the frequency domain, *i.e.*, its *spectral properties*. The spectrum is itself an averaged, time-invariant concept and generalization to a "time-varying" spectrum is somewhat tricky. One aspect of this problem lies in the well known frequency-time uncertainty relation, *i.e.*, that the frequency resolution depends on the time span.

One can argue that it is natural to demand a quicker response time, *i.e.*, better time resolution from the adaptive algorithm, at the high frequency than at the low frequency end. In other words, one seeks a frequency dependent time resolution. This, as such, is nothing new. A typical use of wavelet transform is exactly to have different trade-offs between time- and frequency resolution in different frequency bands.

From this perspective we have examined current parametric adaptation algorithms and investigated if they can offer this desired feature. Details are in [126]. It turned out that the most used adaptation algorithms – Least Mean Squares (LMS) and Recursive Least Squares (RLS) – do not give this kind of trade-off: The time-window for RLS is frequency independent, while for LMS it depends on the level of the spectrum (not the frequency).

The major point of this contribution, however, is that a frequency-time trade-off of the desired type can be achieved also in parametric modelling. The key is to use a Kalman-filter based algorithm with a carefully tailored state noise covariance matrix.

4.8.1 Discrete parameters in linear systems

The problem of estimating discrete parameters in linear systems occurs in many applications. A number of them appears below as active research areas. Conclusions from this work and a general theory is found in [53], [78], [74] and [111].

Segmentation

By segmentation is meant the problem of detecting abrupt changes in the dynamical properties of signals and systems. The goal is to estimate the time instants when these changes occur in a statistical optimal way. The proposed method is model based. The measured signal y_t is described as a linear regression,

$$y_t = \varphi_t^T \theta_t + e_t.$$

The key idea is that the time-varying parameter vector is assumed to be piecewise constant, in contrast to tracking problems where it is commonly modelled as a random walk. The estimate of the change instants in θ_t is found by maximizing the *maximum a posteriori* (MAP) probability or, alternatively, the likelihoods.

This work concerns questions like how to implement the optimal solution, which has exponential complexity in time, in a feasible way. Both effective approximate algorithms and an exact algorithm linear in time have been proposed.

Model selection

Facing the black box modeling problem of a physical process, one has to choose a suitable structure for the model. For linear regression structures, the problem is which regressors should be used. One possibility examined here, besides the well-known Akaike and MDL criteria, is to apply the maximum likelihood method. That is, we take a statistical instead of information theoretic approach, which has been proposed in a number of papers recently. However, there are a number of open questions in the problem formulation before the ML method can be applied, and this is supposed not to be fully understood before. In [110], [73] and [50] a number of different criteria is derived from the ML method, just by changing the problem formulation in the ML method. It turns out that they have completely different properties, where some of them are asymptotically equivalent to Akaike's BIC and the MDL criteria.

Blind equalization

Consider the problem of determining the binary input sequence in the linear regression

$$y(t) = b_1 u(t-1) + b_2 u(t-2) + ... + b_n u(t-n), \quad u(t) = \pm 1.$$

Is it possible to give sufficient and necessary conditions for determining $\{u(t)\}$?

This is the problem of *identifiability in blind equalization*. The linear regression is a model of a transmission channel, often given as such a finite impulse response (FIR) model. The problem is to recover the information transmitted on the channel in terms of symbols from a finite alphabet — not necessary ± 1. This problem often appears in digital communication. The identifiability question is solved for noise-free FIR channels in [23] and [51].

Shortly, a necessary condition is that the input sequence is persistently exciting or order $2n-1$. Compare this to the order n condition for parameter identifiability when the input sequence is known. A sufficient condition involves that certain linear combinations of the true parameter values must not be zero.

Manoeuvre tracking

The problem of manoeuvre tracking and detection for aircraft applications is studied in [70] and [52]. The problem is related to segmentation, and the goal is to find the time instants when the pilot makes a decision of a manoeuvre, which greatly simplifies the tracking problem. A great effort is spent on the modelling question, which is crucial for the performance of the tracker.

Detection

Detection of abrupt changes in the state of a linear system is one of the original and best known example of model based change detection. In [22] an off-line algorithm based on the likelihood ratio test is proposed, which is linear in time instead of the quadratic complexity of the well-known GLR algorithm, where a windowing approximation is used to get linear complexity. Another key feature is that the critical dependence of the assumed noise variance is eliminated by considering it as a stochastic parameter. This implies a much better robustness and less tuning.

4.8.2 Tire–Road Friction Estimation

In a project called "Slip-based Automatic Friction Evaluation" (SAFE) the goal is to estimate the friction between tire and road and supply the driver with this information together with a safety margin calculated from the friction coefficient and forces acting on the car.

As a development platform, a Volvo 850 GLT has been hooked up to a PC with real-time software. The following parts are included in the current prototype.

1. **Sensors.** A key point with this approach is that just standard sensors are used. The needed quantities are: wheel velocities provided by the ABS system, a load signal from the injection system and the brake light signal.
2. **Computations.** The raw data are used to compute parameters related to the motion of the car. Among these, we mention velocity, engine speed, gear level, lateral and longitudinal acceleration, curve radius, yaw rate, relative wheel radii, slip and traction force. Effort is also spent on outlier detection and rejection.
3. **Filtering.** These parameters are used in a Kalman filter to estimate friction related parameters.
4. **Classification.** From extensive test drives on known surfaces, a classifier is constructed. It uses the parameters from the Kalman filter as input and gives the actual surface as output.
5. **Driver interface.** In a current prototype, the driver is informed by the friction and safety margin, defined by comparing the current forces on the car to the maximal values allowed by the friction. As a side product, the driver is also informed about abnormal tire inflation pressure, concluded from the wheel radii computations necessary for other purposes.

An interesting signal processing problem occurs in the filtering step. The basic model is

$$s(t) = F(t)\theta_1 + \theta_2,$$

where $F(t)$ is the traction force and $s(t)$ is the so called slip, defined as the relative difference between the circumferential velocity of a driven wheel and its absolute velocity. The model is valid for small slips (less than 10 permille), and implies that whenever a traction force is needed, the driven wheels rotate somewhat faster than the free-rolling ones. Basically, the parameter θ_1 has a unique value for some important surfaces like dry and wet asphalt, snow and ice.

Now the problem is that both observations on $s(t)$ and $F(t)$ are corrupted by noise, and outliers are very frequent. Next the parameters are time varying. The offset θ_2 is slowly time-varying, while θ_1 is supposed to change abruptly when coming to an ice spot for instance. The solution is to use a Kalman filter connected to a change detector and certain logics.

More details are found in [77], [116], [119] and [124]. In [122] is reported how this setup can be used to estimate rolling and air resistance.

Test drives in Arvidsjaur

Chapter 5

Signal Processing

Under the signal processing heading activities in the areas of sensor array processing and processing of laser range images will be reported. The work on sensor array processing is done by Mats Viberg, Björn Ottersten and Sören Andersson and the work on laser range images is done by Predrag Pucar and Mille Millnert.

5.1 Sensor Array Processing

The interest in performance improvement for direction-of-arrival (DOA) estimation algorithms can result in antenna arrays composed of a large number,m, of sensor elements. Since the computational requirements are directly affected by the dimension of the collected data, the burden increases rapidly with the number of sensors. This increase is at least proportional to the square of the dimension of the collected data. This is the case, *e.g.*, for the popular high-resolution methods based on eigendecomposition of the array covariance matrix. Therefore, in order to reduce the computational complexity of the algorithms it may be useful to introduce some sort of mapping that reduces the dimension of the data set, from m in element space (ES) to r ($r << m$) in the reduced dimension beamspace (BS), before performing the signal processing. Another advantage is that if the transformation matrix is implemented using analog technology, there is a need for only r analog-to-digital converters, in contrast to the m ones needed for ES computations.

One approach to reduce the amount of computations is to employ a linear (matrix) transformation for mapping the full dimension ES data into the lower dimensional BS, and then apply a signal processing algorithm to this new set of data. The main interest is then to analyze under which circumstances it is possible to retain the property of asymptotically achieving the full-dimension Cramer-Rao bound (CRB), while significantly reducing the dimension of the data set used for the DOA estimation. Perhaps somewhat surprisingly, it is possible to obtain very simple analytical expressions for the requirements to be met by an optimal transformation matrix. These expressions rely on knowledge of the functional form of the array (calibrated array of arbitrary geometry) and the true locations of the sources present. This last condition is, however, not limiting the possibilities of using the results derived to outline a design method. If a spatial sector is specified, in which sources of interest are assumed to be located, it is possible for the locations of these sources to be (very close to) optimally estimated in the sense of the full-dimension CRB. The resulting design strategies are further discussed in [6, 128, 2].

Moreover, in order to further examine the nearly optimal design strategy, [65, 2] discusses so-called two-stage methods for DOA-estimation and its performance compared to what is optimally achievable. In [63, 2], an examination is made of an approach for design of BS transformation matrices that address the problem of retaining as much as possible of the ultimate (ES) Cramer-Rao performance in a specified DOA-sector, while also taking into account the sidelobe levels of the BS beam pattern outside this sector. An asymptotic analysis of some beamspace based subspace fitting algorithms for DOA-estimation for a large number of sensor elements can be found in [64, 2].

5.2 Modelling, Estimation and Segmentation of 2D Structures

Segmentation of 2D structures in the context of *model based stochastic techniques* is connected with high, very often unpractical computational complexity. The objective of our work in this field is to design algorithms which might be suboptimal, but not computationally demanding. Algorithms that are essentially one-dimensional, and their extensions to two dimensions are studied.

Two different models have been studied. Jump System and Hidden Markov Models (HMM). The model used is the well known *hidden Markov model*. Estimation of the number of hidden states from observed data, is a problem that is investigated. The state order estimation problem is of general interest and is not specifically connected to image processing. An investigation of three state order estimation techniques for hidden Markov models has been performed.

5.2.1 Segmentation and estimation based on jump models

The work described here is reported in [13] The approach in this work is based on a terrain model where a scanned row, or column, can be decomposed into a sequence of *segments*. Denote the range values of a scanned row by r_k, $k = 1, \ldots, N_C$. The range values within a segment are modeled as the sum of a constant mean value r^0 and local fluctuations u_k, i.e.,

$$r_k = r^0 + u_k. \tag{5.1}$$

For simplicity the local variations u_k are modeled as a sequence of independent, identically distributed (i.i.d.) random variables with zero-mean Gaussian distribution with variance R_u.

The transition from one segment to the next is characterized by a change in the mean value r^0. The length of the segments, and thus also the transition points, are assumed to be random. It will be convenient to model the segment transitions as being controlled by a two-valued, i.i.d. stochastic process ξ_k, with probability density function

$$P(\xi_k = i) = \begin{cases} 1 - q & \text{for } i = 0 \\ q & \text{for } i = 1. \end{cases} \tag{5.2}$$

q is thus the probability that a given pixel is on the boundary between two segments.

The difference in mean range r^0 between two consecutive segments, with transition point k, is modeled as a Gaussian variable δ_k with zero mean and variance R_δ. Now, let r_k^0 denote the piecewise constant function obtained by concatenating the mean values of the segments. The range variations, r_k, over a row are then described by the equations

$$\begin{aligned} r_{k+1}^0 &= r_k^0 + \delta_k \xi_k \quad (5.3) \\ r_k &= r_k^0 + u_k. \quad (5.4) \end{aligned}$$

Instead of a piecewise constant model a piecewise linear model could be used.

Equation (5.1) can be expressed as a *linear regression model*

$$r_k = \theta^T \varphi_k + u_k. \quad (5.5)$$

where

$$\theta = r^0, \qquad \varphi_k = 1 \quad (5.6)$$

The model for the range variations over row (or column) becomes

$$\begin{aligned} \theta_{k+1} &= \theta_k + \delta_k \xi_k. \quad (5.7) \\ r_k &= \theta_k^T \varphi_k + u_k. \quad (5.8) \end{aligned}$$

The rationale for the models above is that by letting the local fluctuations in range be described by the "noise" u_k it will be possible to lump adjacent pixels with approximately the same value in range r_k together into segments. The boundaries between segments then correspond to range variations which can not be attributed to the random variations in u_k, but must be "explained" as changes in the mean range or slope, i.e., in the parameter vector θ_k. The compromise between what will be considered as "normal" random variations within a segment and jumps in the parameter θ_k is given by the relative magnitudes of the variance of u_k on one hand and the covariance R_δ together with the jump probability q on the other.

In [13] it is shown how the image can be segmented based on the above model. The segmentation technique uses a bank of Kalman filters and the AFMM search method.

5.2.2 Segmentation and Estimation Based on Hidden Markov Models

The work presented here is reported in [31]. We begin with the introduction of the concept of hidden Markov models (HMM). A HMM is a doubly stochastic process with one underlying process that is *not* directly observed, but can only be observed through another set of output processes that produce the observed data. The underlying hidden process is a Markov chain, and the processes that produce the observed data can be modeled by a variety of models, of which some will be mentioned here.

A *Markov chain* z_t is a special case of a Markov process, with the additional property that it takes values in a finite set $\mathcal{M} = \{1, \ldots, M\}$. It is specified in terms of its stationary distribution

$$q_i = P(z_t = i),$$

where z_t denotes the state of the Markov chain at time instant t, and its transition probabilities

$$q_{ij} = P(z_{t+1} = j | z_t i) \qquad i, j \in \mathcal{M}.$$

The second part of the HMM is the observed process. Loosely speaking, the observed process is a sequence of random variables generated by a family of probability density functions (discrete or continuous), e.g. the output of a dynamic linear system driven by white noise. As one of the objectives with our work is to design simple and fast algorithms that can be used in real time applications, we concentrate on systems that can be written as regression models

$$y_t = \varphi_t^T \theta + e_t,$$

where e_t is Gaussian white noise. Despite this simplifying assumption a variety of useful models are covered.

We have thus ended up with a bank of systems labeled 1 through M, and a Markov chain controlling which system produces the output at a specific time instant. There are a number of interesting issues emerging from the model setup above. For example, how to using data, estimate:

1. parameters in the models producing the observed output data

2. the transition probabilities of the hidden Markov chain
3. the state sequence of the hidden Markov chain
4. the number of states of the hidden Markov chain.

There are two main approaches addressing the questions one through three, namely; the Baum-Welch reestimation algorithm and a family of methods called Bayesian algorithms. The Baum-Welch reestimation algorithm is essentially a “numerical” algorithm used for finding the model parameters and state sequence maximizing the likelihood of the data. Bayesian methods have in common that the maximum *a posteriori* estimate of the state sequence

$$\hat{Z}^N = \arg\max_{Z^N} P(z^N|y^N)$$

is sought. The problem is computationally unpractical, so suboptimal solutions have to be used. To find the optimal estimate all sequences z^N have to be considered. The way out of this problem, as we implicated, is to cut off sequences with low probability. As an estimate of the state state sequence, the most probable of the surviving sequences, is used.

The extension of the above 1D model to two dimensions is performed using the 2D equivalent of Markov chains, namely *Markov fields*. A Markov field is described by the following expression

$$P(z_{i,j}|\text{whole image}) = P(z_{i,j}|\text{small neighborhood}),$$

where $z_{i,j}$ is the field value at site (i, j). Since we want to apply the ideas from the 1D algorithms to preserve the computational advantages if compared with often used methods in statistical image processing (simulated annealing, graduated non-convexity type of algorithms *etc.*), we have to simplify the Markov field model to non-symmetric half-plane (NSHP) Markov chain, see Figure 5.1.

Using the simplified 2D model the probability $P(\text{complete image} \mid \text{data})$ can be calculated recursively, and the same ideas with suboptimal algorithms as in the 1D case can be used.

The fourth issue mentioned in the introduction; estimation of the number of hidden states, is also studied in this work. One of the novel approaches is to use the predictive least squares (PLS) to estimate the number of hidden states. PLS is a modification of the usual least squares method in the sense that PLS uses "honest" prediction only. Some kind of ordering of the data has to be introduced, otherwise the word "honest" has no meaning. In the 1D case the natural ordering is time. The idea is to use only data up to time instant t when predicting y_{t+1}. In this way a new loss function is obtained

$$V_{PLS} = \sum_{t=1}^{N} (y_t - \hat{y}_{\theta_t}(t))^2.$$

One interpretation of PLS is that *cross validation* is performed in every time step. The loss function can be calculated using different numbers of hidden states. The number that gives the lowest V_{PLS} is chosen as the estimate of the number of hidden states. We have in this work also investigated maximum *a posteriori* estimation of the number of hidden states, and application of MDL to the same problem.

5.2.3 Segmentation of LADAR Images

One application of our work in the field of modeling, estimation and segmentation of 2D structures, is segmentation of laser range radar (LADAR) images. A LADAR is used for collection of a "distance map", for example of a part of the terrain. The objective is to segment the image to find objects that differ from the background. This segmented image is then used as a starting point for further classification, object recognition, tracking *etc.*

The setup in the experiment presented here, is the following. The test image is presented in Figure 5.2.

There is a shield in the center of the image. Note that the z-axis is the distance to the object. If the distance is constant, *i.e.*, there is a vertical object in the field of view of the laser, the result will be an horizontal area in the laser range image. Further, there is one more object in test image #1, namely bushes in the upper right corner of the image.

A NSHP Markov chain with two states is used in the segmentation of the test image. We have also assumed a very simple observed process model, namely

$$y_{i,j} = \theta(z_{i,j}) + e_{i,j}.$$

This means that we model the distance with a constant, corrupted by white noise. The abrupt changes in the image are taken care of by the use of multiple models (two in this case). The resulting segmentation is shown in Figure 5.3.

Figure 5.1: Set of sites associated with the NSHP Markov chain.

Figure 5.2: Test image – vertical shield in the terrain.

Figure 5.3: Resulting segmentation of the test image using the 2D Bayesian algorithm.

Chapter 6

Differential Algebra and Nonlinear Systems

A general way of looking at models of nonlinear systems is to regard them as mathematical relationships between a number of physical variables $w_1, \ldots, w_N$. In general the mathematical description will contain an unstructured mixture of differential and static relations. It is a central problem in modeling and nonlinear system theory to find standardized descriptions that permit analysis and control synthesis. One such description is the standard state space form

$$\dot{x} = f(x, u), \quad y = h(x, u)$$

where x, y and u are suitable subsets of the physical variables $w_1, \ldots, w_N$. It is however well known that this description is too specialized, in the sense that many physical systems can not be described globally in such a way. If all mathematical relationships between the variables are polynomial in the variables and their derivatives, then there exists a powerful mathematical theory, *differential algebra*, for describing and analyzing the system.

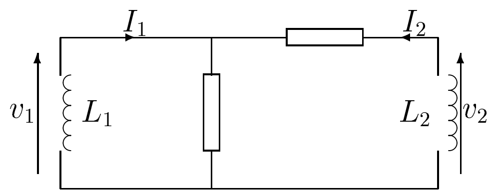

Figure 6.1: Electric circuit with nonlinear resistors and inductors

6.1 Models in differential algebra

In recent years several modeling and system theoretic problems have been attacked using differential algebraic methods. A survey of these developments was given in [43]. Basically there are two points of view, an abstract one where systems are described in terms of differential field extensions, and a constructive one where they are described in terms of so called characteristic sets. A characteristic set is a set of differential equations with a simple structure, from which the solutions of the original physical relationships can be generated. State space equations are just special cases of characteristic sets. Even if a system has a state space description, there might be alternative descriptions, in terms of other characteristic sets, that show up certain properties. For instance, the system

$$\begin{aligned} \dot{x}_1 &= x_2^2 \\ \dot{x}_2 &= u \\ y &= x_1 \end{aligned} \tag{6.1}$$

can also be described by the characteristic set

$$\ddot{y}^2 - 4u^2\dot{y} = 0, \quad 2ux_2 - \ddot{y} = 0, \quad x_1 - y = 0 \tag{6.2}$$

The second set of differential equations shows that the state is observable if the input is not identically zero. It also gives a direct relation between input and output with the state eliminated.

An example that is considered in [43] is shown in Figure 6.1. The resistors are assumed to be nonlinear elements, where the current i is given in terms of the voltage v, by

$$i = g(v)$$

The system is then described by the equations

$$\begin{aligned} g(L_1\dot{I}_1) + I_1 + I_2 &= 0 \\ g(L_1\dot{I}_1 - L_2\dot{I}_2) - I_2 &= 0 \end{aligned} \tag{6.3}$$

which is not a state space description. If g is the polynomial

$$g(v) = \frac{v^3}{3} - v$$

it is possible to calculate the characteristic set

$$A_1 = 0, \quad A_2 = 0$$

where the differential polynomials A_1 and A_2 are defined by

$$A_1 = L_1\,\dot{I}_1 - \frac{{L_1}^3\dot{I}_1^3}{3} - I_1 - I_2$$

$$A_2 = 3\,{L_1}^2\dot{I}_1^2 L_2\,\dot{I}_2 - 3\,L_1\,\dot{I}_1\,{L_2}^2\dot{I}_2^2 + {L_2}^3\dot{I}_2^3 - 3\,L_2\,\dot{I}_2 + 6\,I_2 + 3\,I_1$$

6.2 Observability and Identifiability

Above, in (6.1) and (6.2), an example was shown where observability was decided, starting from a state space description. The idea can be used with any polynomial system description. It can also be extended to identifiability, regarding parameters as constant states. In [26] it was shown that certain parameterizations are canonical, *i.e.* the parameters are globally identifiable, except for a small set of singular solutions to the differential equations. An example of such a parameterization is

$$\ddot{y} + \theta_1 u\dot{y}^3 y^2 + \theta_2\dot{y}y + \theta_3\dot{y} + \theta_4 uy + \theta_5 u = 0$$

The parameters θ_1,..,θ_5 are automatically identifiable, since they are the coefficients of monomials that are lower than $\ddot{y}$.

The characteristic set structure which is used to prove identifiability can also be used to derive a robustly convergent identification algorithm, see [46] and[112] and the chapter on identification.

6.3 Constructive Algebraic Geometry for Nonlinear Systems

If we consider the class of nonlinear systems where all nonlinearities are polynomial or rational it seems rather natural to employ methods from algebraic geometry or, as above, differential algebra, to study them. This has been done frequently earlier in the literature, but recently we have obtained access to efficient computational tools in this field.

The most popular method in elimination theory today are so called Gröbner bases (gb). These are, in some sense, the analogue of Gaussian elimination for systems of polynomial equations. Algorithms for computing gb are available for instance in the symbolic algebra programs Maple, Axiom and Reduce.

In nonlinear state space theory gb can be of great help, *e.g.* to find the input-output relation for a rational control system in state space form, or to investigate observability and state space transformations. Elements from the theory of gbs have been used to derive theorems for the generic structure of a polynomial system in state space form [76].

A Maple program called POLYCON has been written for state space analysis of polynomial and rational systems using gb [66, 99]. POLYCON is available by anonymous ftp. In [98] we describe some of the mathematical "tricks" that are used in POLYCON, in order to enhance computational efficiency. Connections with the problem known as *implicitization* in computational algebraic geometry are made in [123].

The classical problem of *realizing* a nonlinear input-output differential equation has been investigated. Given an algebraic differential equation (d.e.) in y the question of determining if this d.e. is an input-output equation of a system in rational state space form is strictly harder than a famous unsolved problem in algebraic geometry, namely the one of determining whether a given affine hypersurface is unirational or not. So the solution to this problem is unfortunately not constructive yet.

In some problems it is extra important that the solutions obtained be real. Here methods from real algebraic geometry, such as quantifier elimination and cylindrical algebraic decomposition could be used. In [113] an optimization problem in Lyapunov theory is formulated as one of real algebraic geometry. The basic problem is that of determining critical levels of local Lyapunov functions. Unfortunately the computational complexity is very high in real algebra, so it could be better to use gb here too, together with some tricks and usage of prior knowledge.

6.4 Nonlinear Controllers of "Fuzzy" Type

There is a class of nonlinear controllers that have become extremely popular, mostly in applications, during the last few years. These are so called "fuzzy controllers" which use fuzzy logic to specify a certain nonlinear function which is then used in the feedback law. Unfortunately, fuzzy controllers are not yet very well understood from a theoretical point of view and much of the analysis made in the application reports merely consists of some simulation results. During the year some effort has been spent in order to understand fuzzy control from a more classical, control theoretical perspective [29].

The first thing needed is then a mathematical description of the controller. It turns out that such analytical expressions for the control law exist, contrary to what is commonly believed, for a sufficiently interesting class of controllers. A Maple package called FuzzyCAT [121] has been developed to support mathematical analysis of fuzzy controllers. In FuzzyCAT it is possible to obtain closed expressions for the control law, even if its specification involves some symbolic parameters. Furthermore, FuzzyCAT contains functions for classical nonlinear system analysis such as the circle criterion and describing functions. FuzzyCAT is available by anonymous ftp.

Chapter 7

Modelling

7.1 Physical Modelling

The term 'physical modelling' is in a sense quite peculiar. It suggests the existence of a modelling activity which is completely free of physical considerations. One could ask if there is any engineering activity that completely avoids confrontation with physics.

The reason why this term has been coined is the need to distinguish between activities that are oriented towards the quantitative and numerical side of modelling rather than the qualitative and structural. Even in the case of system identification, we certainly should incorporate as much physical insight as available before applying our numerical estimation algorithms. A physical modelling approach, however, is solely aiming at finding formal methods to systematically use available physical insight, often qualitative to its nature, to derive a mathematical *model structure.*

Typically the ultimate goal of a modelling exercise is to derive a completely specified quantitative mathematical model, and therefore physical modelling is typically combined with system identification [34].

7.2 The General Approach

The classical engineering approach to physical (systems) modelling is best characterized as a three phase modelling paradigm. First, we have the *reticulation*, in which phase the observed physical system is conceptualized in terms of physical mechanisms or effects and their interactions. That is, the system is abstracted into a set of idealized *engineering concepts* such as resistance, capacitance, inertia *etc* . A network model consisting of interconnected *physical mechanisms* is then created. At this point, those properties of the observed system that are considered to be relevant to the purpose of the model are distinguished without going into mathematical details.

Second, we have the *mathematical characterization* in which phase the mathematical relations that characterize the physical mechanisms are specified. It is due to proper definition of the physical mechanisms that this step can partly be automated: the engineering concepts and their interactions are characterized by their mathematical constraint relations, *i.e., constitutive relations*. This phase constitutes a second step of abstraction away from the observed system.

Third, we have the *compilation* in which phase the above relations are compiled into a suitable computational description, which can then be used for model analysis by completely automated numerical methods.

The bond graph formalism provides significant support in all these three phases. In the system reticulation phase, bond graphs significantly support the modelling task by providing a small and well defined set of generic physical mechanisms. These elements are motivated from first principles of energy conservation and give an efficient guide as to which are the potentially relevant aspects of the observed system; they provide the engineer with an adequate and efficient *ontology*. They also correspond closely to primitive engineering concepts within several domains and applications.

Hence, bond graphs *explicitly* represent the conceptual engineering knowledge used to develop the mathematical model. This knowledge is often left implicit, due to the emphasis on the mathematical aspects of modelling, and typically only the final mathematical result is presented. However, in order to enable and facilitate systematic model validation and modification, an explicit representation of this knowledge is crucial.

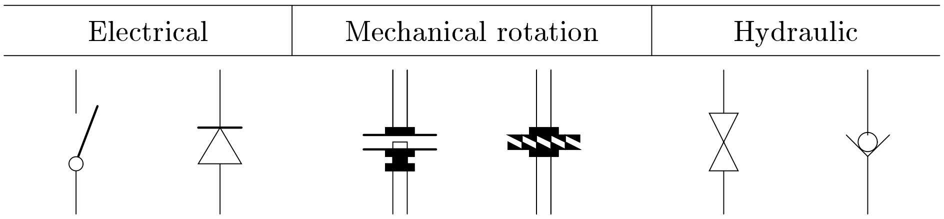

Figure 7.1: Some explicit discrete devices.

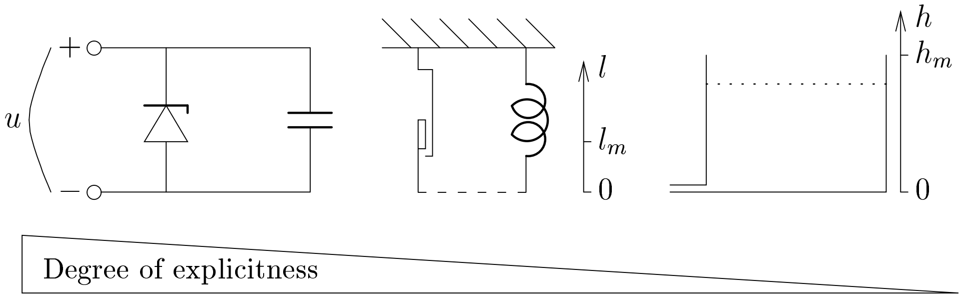

Figure 7.2: A spectrum of mode switching phenomena.

7.3 Hybrid Systems

Abrupt changes in the dynamic behaviour of physical systems are ubiquitous in engineering applications. In fact, many engineering devices are designed intentionally to obtain near ideal switching behaviour *e.g.* electrical relays, diodes, mechanical clutches, free wheeling devices, hydraulic valves, hydraulic check valves *etc* ; see Figure 7.1. In all these cases, the devices are intentionally designed to introduce an abrupt change in the overall dynamics of the systems they are installed in. With abrupt change we here mean a change several magnitudes faster than the fastest dynamics of the overall system.

Moreover, abrupt changes may occur as an implicit property of engineering systems, *i.e.,* phenomena not due to any explicitly distinguishable 'device' or 'component'. In Figure 7.2 a spectrum of different occurrences of such discrete phenomena is shown.

Characteristic for all the examples in Figure 7.2 is the existence of three distinct *modes of operation*: one mode of continuous dynamic behaviour (of order one) and two other modes in which the 'state' variables are fixed to constant values (order zero). This is due to physical effects which change the operating mode by restricting the energy storing capability of the systems when certain conditions are met. The important observation to be made is that the basic energy storing property of the systems is never actually changed. Rather the *range* over which the systems can perform this behaviour is affected by the discrete mechanisms. Hence all these mode transitions can be viewed as changes in the (energetic) interaction structure of the overall system. In fact, we propose this as our definition of a *mode switching dynamic system*, or what has lately been referred to as a *hybrid system* [47].

7.4 Reticulating Hybrid Systems

We have noticed that discrete phenomena typically affect the model of the physical structure in the same manner as do concrete changes of the structure at the physical level. This explains why the term 'variable structure system' is sometimes used in this context. This will inevitably and drastically complicate the reticulation phase unless a mode invariant structure can still be found.

It is clear that some additional model structure is needed to represent models across several distinct modes of behaviour. At the mathematical level, the associated structuring information must in one way or another be specified by the logical conditions that control the transitions between modes of continuous differential and algebraic (DAE) systems. The logical conditions are the *invariants* that represent the switching actions at this level; see *e.g.* the model tree representation in Figure 7.3. However, the mathematical perspective is just one side of the coin.

In the engineering practice we know that a *physically* based conception of the observed system is fruitful in guiding the formulation of the equations. This conceptual level, that is closer to the observed phenomena than the abstract mathematical description, assists in making explicit the relevant modelling assumptions, whereas the generation of the actual equations becomes a matter of routine. This immediately raises the question whether it

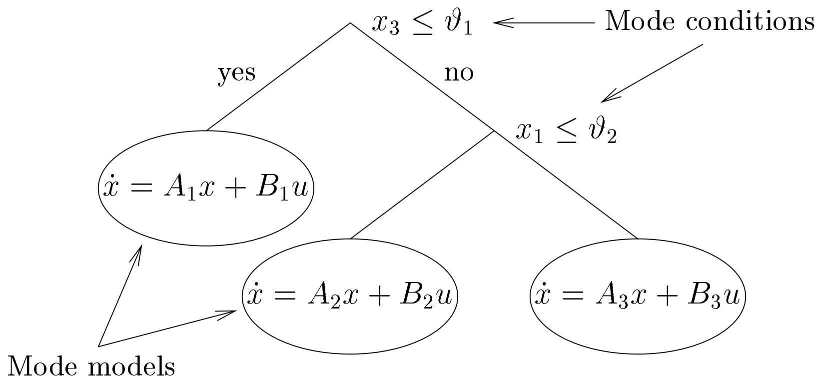

Figure 7.3: A model tree as a mode invariant representation.

is possible, and if so, how to extend the set of physical concepts to sanction this distinction.

In [37, 47] we have presented a new candidate bond graph concept, the *ideal switch* (SW) element, for the very purpose of representing discontinuous transitions. We have shown that the switch concept actually extends the modelling power of bond graphs, with no trade-offs in conceptual clarity, to mode switching systems as well. We have also shown how the model structure as derived by such a *switched bond graph* may be used to provide active support in online detection of mode transitions in hybrid systems [38].

The SW-element has two distinct *states*, namely *effort* ($\mathcal{E}$) and *flow* ($\mathcal{F}$) state. In state $\mathcal{E}$ it acts as an ideal effort source with zero output and in state $\mathcal{F}$ it acts as a flow source, also with zero output. Note that the zero-valued sources have a particular *qualitative* meaning as particular boundary conditions. We have chosen the mnemonic SW to represent the switch, noticing the close relation with the ideal sources. An immediate and interesting consequence of this definition is that the element will affect the overall causal structure of the model as the state of the switch changes.

Note that the SW-element – being a source type of element – has no constitutive relation in the ordinary meaning; it does not relate the effort and flow variables with each other. Its state is however determined by a *control structure* $\Psi(\tau_e, \tau_f)$ which may be expressed in terms of a simple two-state transition system. Here the boolean transition conditions τ_e and τ_f denotes any boolean (in-)equality relations between any of the continuous state variables in the model.

7.5 An Example Hybrid System

Consider the hybrid system in Figure 7.4 (left). We are interested in studying the touch-down-process of this light aircraft, and therefore reticulate the system as depicted in the schematic diagram in Figure 7.4 (right). Applying the systematic method of mapping mechanical schematic diagrams to bond graphs, we immediately end up in the switched bond graph as depicted in Figure 7.5 (left). Note that the mapping procedure for standard bond graphs can be applied on switched bond graphs without any modification.

Generating the four potential causal bond graphs, *i.e.,* the four computational structures, is now completely straightforward using standard causality propagation rules. The overall mode structure of the system now becomes a four-state transition system and can be obtained from the two control structures in Figure 7.5 (right) by applying standard transition system composition. We now have a complete computational model of the touch-down-process.

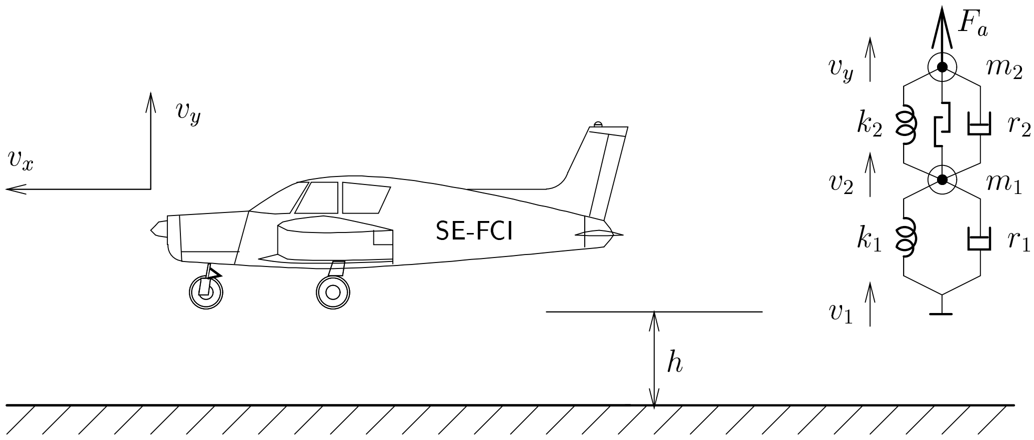

Figure 7.4: A hybrid system (left) and a reticulation of the same (right). m_1 is the mass of the wheel and damper sub-system and m_2 is the mass of the mainframe. F_a is the aerodynamic force acting on the mainframe.

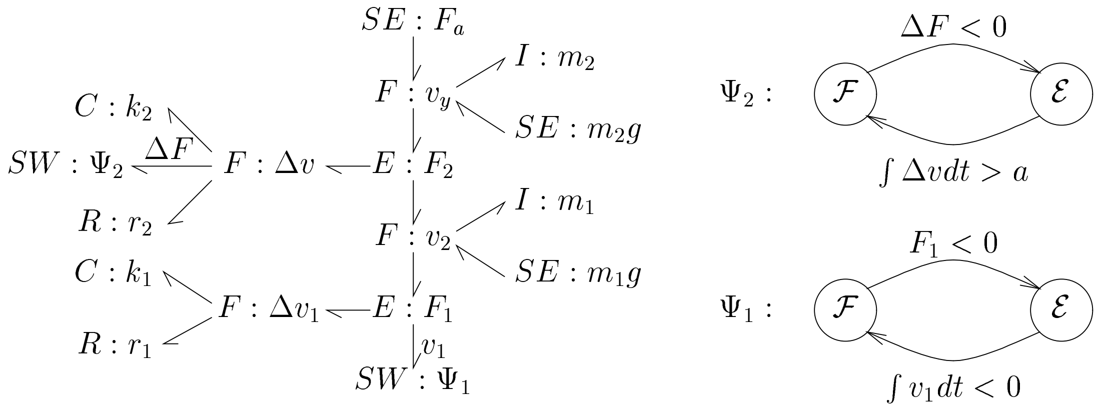

Figure 7.5: The acausal switched bond graph (left) and the control structures (right) of the landing aircraft system.

Chapter 8

Discrete Event Systems

Symbolic Control

Symbolic processes are processes that allow an *exact* finite description. Some well known descriptions include: Finite State Systems, Petri Nets, Polynomial Dynamical Systems. The main applications are various forms of sequential control such as:

- Strategic control for plants which include start up, shut down and error recovery.
- Proper sequencing of events in chemical processes and work cells. In this case "proper" should include the enforcing of various constraints such as safety measures and perhaps ordering of events.

The algorithmic treatment of these processes and their controls is decidedly of a different flavour compared to traditional control, in that exact representations and computations are used. This is a strong departure from the approximate, numerical analysis based paradigm usually followed. In this area this is quite natural since there is no notion of approximation anyway, *i.e.* the only topology is typically the trivial one of equality.

Formally all models can still be stated as state space models, *i.e.*

$$x(k+1) = f(x(k), u(k)), \quad y(k) = g(x(k), u(k))$$

although there can be a wide range in exactly how this state space looks[1]. At a first level one could separate these according to the size and structure of their state or memory. This yields the usual formal language based hierarchy with Turing equivalent systems at the top and regular languages at the bottom. From a descriptive point of view one would of course like to work with models close to the top in this hierarchy – and that is quite feasible if the only objective is to simulate. If the objective is to analyse and synthesize systems then one quickly finds that most properties are undecidable. For these reasons one would hope that finite state based systems are good enough for many real world problems.

When concentrating on finite state based systems one immediately finds out that finite numbers can be very big. In practice this comes from the fact that one connects several subcomponents to form the complete system. If these subcomponents interact or we put constraints on these together we will have to form the product state space, *i.e.* the set of all tuples with components in the respective subsystems. Having p subsystems with n states in each would then yield a combined state space of n^p states. For these reasons the focus is very much on complexity.

Simplified Action Structures (SAS)

Simplified action structures is another notation for finite state based systems. The states are given as tuples:

$$x = [x_1, x_2, \ldots, x_n]$$

and each x_i resides in some finite domain $\mathcal{S}_i$. The controls or inputs are termed *actions* and their affect on the system is described through *pre-*, *post-* and *prevail-conditions*. The pre- and post-conditions tells us the actual effect of the action and the prevail condition can detail further conditions which must be satisfied during the execution. Without further restrictions this is of course exactly the set of finite state systems.

[1]E.g. as formulas in λ-calculus, machine state in Turing machines or marking vectors in Petri Nets *etc.*

We have focused on the *planning problem*, that is, the problem of finding a control sequence which transforms a given initial state into a desired final state. It is easy to show that without further restrictions the complexity of planning increases exponentially with the number of state variables. This is because the state space is exponential in size in terms of the number of state variables, and there are systems that force you to traverse the entire state space to reach your goal. Since a lower bound of the algorithm is derived from the size of the output it is then of course impossible to find the plan in polynomial time.

The set of problems analysed in this study basically excludes such processes as described above. The exact class studied is defined through explicit conditions on the actions and the details can be found in [4, 93]. In these papers there are also algorithms for solving the planning problem under different restrictions. The algorithms are proved to be correct and complete. They always return a minimal plan (in terms of length) if there is one. Furthermore the generated plan shows maximal parallelism. The complexity of the algorithm is proved to increase polynomially with the number of state variables. A similar algorithm can be used for testing reachability for a restricted class of problems [96].

Polynomial Dynamical Systems over Finite Fields

This work focuses on using polynomial dynamical systems over finite fields as a system description. These systems all have the familiar form:

$$x(k+1) = f(x(k), u(k)), \quad y(k) = g(x(k), u(k))$$

where f and g are vectors of polynomials over some finite field.[2]

In terms of descriptive power these are exactly the set of finite state systems, this is easily realized through the use of Lagrange interpolating polynomials. This has the following consequences:

+ We can map all finite state based formalisms into this one. (We don't loose any of these systems.)

[2]One could of course drop the assumption about *finite* fields above and thus obtain general polynomial dynamical systems, these are described elsewhere in this report.

- We can map all finite state based formalisms into this one. (We also get all the hard systems.)

Systems based on polynomials over finite fields have a structure that is similar to both ordinary polynomial nonlinear systems as well as Boolean systems. The structure of these polynomial rings has been characterized in an earlier sequence of studies and some of the results include; a version of Hilbert nullstellensatz (for the geometric connection) and that these rings are principal (this gives us more choices in the computational formulation of analysis and design problems). An algebraic completeness proof for propositional logic has also been given as well as an automatic way of generating proof systems for (finite) multivalued logics.

These algebraic results form the backbone of further analysis and design formulations in this domain. An outline of some of these can be found in [117].

Appendix A

Personnel

Lennart Ljung is professor and head of the control group since 1976. He was born in 1946 and has his Ph.D. in Automatic Control from Lund Institute of Technology. He is an IEEE fellow, a member of the Royal Swedish Academy of Engineering Sciences, and an IFAC advisor. He also is an associate editor of several journals.
`email: ljung@isy.liu.se`

Torkel Glad was born in Lund, Sweden in 1947. He received his M.Sc. degree in engineering physics in 1970 and the Ph.D. degree in automatic control in 1976, both from the Lund Institute of Technology, Lund, Sweden. Since 1988 he is Professor of Nonlinear Control systems in the department. His research interests include Nonlinear Systems, algebraic aspects of System Theory and Optimal Control.
email: `torkel@isy.liu.se`

Mille Millnert is a Lecturer in the department. He was born in 1952 and received his M.Sc. in 1977 and his Ph.D. in Automatic Control 1982 from Linköping University. His research interests are Model Based Signal Processing, Parameter Estimation and the Combination of Numerical and Symbolical techniques in Signal Processing and Control.
email: `mille@isy.liu.se`

Svante Gunnarsson was born in 1959. He received his M.Sc. in 1983, his Licentiate's degree in 1986 and his Ph.D. in 1988 all from Linköping University. Since 1989 he is Lecturer at the department, and his research interests are system identification and adaptive control.
`email: svante@isy.liu.se`

Alf Isaksson was born in 1959. He is Lecturer in the department. He received his M.Sc. in 1983 and his Licentiate's degree in 1986 and Ph.D. in 1988, all from Linköping University. His research interests are System Identification and Signal Processing. He was a lecturer in the department 1989-1992, and is now with the Automatic Control Group and The Royal Institute of Technology in Stockholm.
`email: alf@elixir.e.kth.se`

Kent Hartman was born in 1951. He received his M. Sc. in 1977 Applied Physics and Electrical Engineering at Linköping University, Department of Biomedical Engineering. He is an associate lecturer in the Control Group.
`email: hartman@isy.liu.se`

Mats Viberg was born in 1961. He is a Research Associate at the department. He received his M.Sc. in 1985, his Licentiate's degree in 1987 and his Ph.D. in 1989, all from Linköping University. His research interests include Sensor Array Processing, Adaptive Signal Processing and Parameter Estimation. Since September 1993 he is Professor of Signal Processing at Chalmers Institute of Technology, Gothenburg.
email: `matsv@isy.liu.se`

Tommy Svensson was born in 1963. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1986 and his Ph.D. in 1992 both from Linköping University. His research interest is nonlinear systems. He is currently employed at Bofors Underwater Systems, Motala, Sweden.
email: `tommy@isy.liu.se`

Inger Klein was born in 1964. She received her M.Sc. in 1987, her Licentiate's degree in 1990, and her Ph.D. in 1993, all from Linköping University. She is currently a research associate at the department. Her research interest is Discrete Event Systems and Sequential Control.
email: `inger@isy.liu.se`

Krister Forsman was born in Stockholm in 1963. He got his M.Sc. in Applied Physics and Electrical Engineering in 1987 and his Ph.D. in 1991, both from Linköping University. He is currently a research associate at the department. His research interests include algebraic and algebro-geometric aspects of nonlinear systems theory, especially in connection with computer algebra.
`email: krister@isy.liu.se`

Ke Wang Chen was born in 1960 and came from Shanghai, China in September 1986. She graduated from East China Normal University with B.Sc. in Mathematics in 1982. She received her Licentiate's degree in 1991 from Linköping University. She spent the 1991/92 academic year at University of California, Berkeley as Visiting Scholar. Her research interests include applications of differential algebra to nonlinear systems and transformer saturation problems.
`email: ke@isy.liu.se`

Fredrik Gustafsson was born in 1964. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1988, his Licentiate's degree in 1990 and his Ph.D. in 1992. He is currently a Research Associate at the department. His research interests include segmentation, blind equalization, model structure selection and aspects on estimation of discrete parameters in linear systems.
`email: fredrik@isy.liu.se`

Sören Andersson was born in 1964. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1988 and the Licentiate's degree in 1990, and his Ph.D. in 1992, all from Linköping University. His research interests are in array processing and parameter estimation.
`email: soren@isy.liu.se`

Håkan Hjalmarsson was born in 1962. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1988 and his Licentiate's degree in 1990 and his Ph.D in 1993, from Linköping University. He spent 1991/92 at California Institute of Technology and is now a research associate. His research interests are in the area of system identification, especially model quality issues.
`email: hakan@isy.liu.se`

Jan-Erik Strömberg was born in the deep dark forests of Dalarna, the forest called Gagnef, in 1963. His hobbies are dogs, flying objects and coffee. He received his M.Sc. in Computer Science and Engineering from Linköping University in 1988. Trees and dogs still play an important role in his life, since they form an integral part of his research in non-conventional system identification and modelling. He is a bit fuzzy and frugal.
`email: janerik@isy.liu.se`

Roger Germundsson was born in 1965. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1988 at Linköping University. He spent 1988/89 at Stanford University at the Information Systems Laboratory. He is currently a PhD candidate at Linköping University. His research interests include areas where symbolic computation can be expected to have an impact such as nonlinear polynomial dynamical systems, polynomial dynamical systems over finite fields and sequential control.
`email: roger@isy.liu.se`

Jonas Sjöberg was born in 1964. He received his M.Sc. in Applied Physics in 1989 from Uppsala University. In 1993 he received is Licentiate's degree from Linköping University. His current research interest is in the field of nonlinear identification with neural networks.
`email: sjoberg@isy.liu.se`

Torbjörn Andersson was born in 1967. He received his M.Sc. in Applies Physics and Electrical Engineering and in 1990 from Linköping University. His current research interest is in the field of identification.
`email: toand@isy.liu.se`

Predrag Pucar was born in 1965. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1990 at Linköping University. He is currently a PhD student and his research interests are signal and image segmentation.
email: `predrag@isy.liu.se`

Peter Lindskog was born in 1965. He received his M.Sc. in Computer Science and Engineering from Linköping University in 1990. His current research interests include non-conventional system identification and various aspects of modelling.
email: `lindskog@isy.liu.se`

Håkan Fortell was born in 1967, and he received his M.Sc. degree in Applied Physics and Electrical Engineering at Linköping University in 1991. His current research interest is nonlinear systems.
email: `hafor@isy.liu.se`

Tomas McKelvey was born in 1966. He received his M.Sc. degree in Electrical Engineering at Lund Institute of Technology in 1991. His current research interests are in System Identification.
email: tomas@isy.liu.se

Anders Ericsson was born in 1967. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1992 at Linköping University. His current research interest is in the field of estimation.
email: ericsson@isy.liu.se

Jonas Plantin was born in 1966. He received his M.Sc. in Applied Physics and Electrical Engineering from Linköping University in 1992. His current research interest is in the field of discrete event systems.
email: plantin@isy.liu.se

Johan Gunnarsson was born in 1967. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1992 at Linköping University. His current research interest is in the field of discrete event systems.
`email: johan@isy.liu.se`

Sten Granath was born in 1951. He received his M.Sc. in 1975 from Linköping University, Department of Applied Mathematics.
`email: granath@isy.liu.se`

Hüseyin Akcay was born in Antalya, Turkey in 1958. He received Engineer degree from the Istanbul Technical University in 1981, M.Sc. degree from Massachusetts Institute of Technology in 1988, Ph.D. from the University of Michigan in 1992, all in Mechanical Engineering, and M.A. in Mathematics from the University of Michigan in 1991. From 1982 to 1983, he worked in the State of Hydraulic Works, Ankara, Turkey. He is currently a postdoctoral researcher in the Department. His research interests are in control-oriented system identification and signal processing.

Qinghua Zhang was born in Shenyang, China. He spent the autumn of 1992 at our department as a guest researcher.

Patrik Lägermo was born in 1965. He received his M.Sc. in Applied Physics and Electrical Engineering 1989 at Linköping University, Department of Electrical Engineering. As a research engineer he is responsible for the computer network and the laboratory equipment.
`email: patrik@isy.liu.se`

Ingegerd Stenlund and Ulla Salaneck are secretaries for the control group. They are both 21 years of age, which you can see from last year's quiz. Thank you Professor Godfrey!
`email: ingegerd@isy.liu.se and ulla@isy.liu.se`

Appendix B

Courses

B.1 Undergraduate Courses

M.Sc. (civ.ing.)-program

Automatic Control M (Reglerteknik M) Basic course for the Mechanical Engineering Program. 140 participants. Lecturer: Håkan Hjalmarsson.

Control Theory I (Reglerteori I) Advanced course for the Industrial Engineering and Management Program. Sampled data systems, stochastic control, system identification. 60 Participants. Lecturer: Svante Gunnarsson.

Control Project Laboratory (Reglerteknisk projektkurs) For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Modelling and identification of laboratory processes. Controller design and implementation. 26 Participants. Lecturer: Krister Forsman.

Automatic Control M, advanced course (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Sampled data systems, Nonlinear systems, Signal processing. 20 participants. Lecturer: Torkel Glad.

Modelling and Simulation (Modellbygge och Simulering). For the Applied Physics and Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 110 participants. Lecturer: Torkel Glad.

Digital Signal Processing (Digital Signalbehandling). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Spectral analysis, Filtering, Signal Modeling, Wiener and Kalman filtering, Adaptive filters. 180 participants. Lecturer: Mille Millnert.

Automatic Control Y (Reglerteknik Y). Basic course for the Applied Physics and Electrical Engineering and Computer Science and Engineering Program. 180 participants. Lecturer: Krister Forsman and Mille Millnert.

Modelling of Industrial Systems (Modellering av Industriella System). For the Computer Science and Engineering Program and Industrial. Physical system modelling, Bond Graphs, Identification, Simulation. 40 participants. Lecturer: Svante Gunnarsson

Control Theory Y (Reglerteori Y). Advanced course for the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Sampled data systems, stochastic control, LQG-control with LTR, nonlinear systems, optimal control. 140 participants. Lecturer: Lennart Ljung.

Automatic Control I (Reglerteknik I). Basic course for the Industrial Engineering and Management. 150 participants. Lecturer: Fredrik Gustafsson.

Digital Control (Digital Styrning). For the Applied Physics and Electrical Engineering, Computer Science and Engineering and Industrial Engineering and Management Programs. Numerical control, binary control and PLCS, process computers and applications of digital process control. 185 participants. Lecturer: Lars Nielsen

B.2 Graduate Courses

Linear Systems. Lecturer: Torkel Glad. Literature: T. Kailath: *Linear Systems*, Prentice Hall, Inc. Englewood Cliffs, N.J. 1980.

Adaptive Control. Lecturer: Lennart Ljung. Literature: K.J. Åström and

B. Wittenmark: *Adaptive Control*, Addison-Wesley, 1989.

Robust Control. Lecturer: Lennart Ljung. Literature: J. M. Maciejowski: *Multi-variable Feedback Design*, Addison-Wesley, 1989.

Practical Control' Lecturer: Krister Forsman.

Appendix C

Computers and Laboratory Equipment

Computers and Laboratory Equipment

The Automatic Control group uses an Ethernet based computer network with Sun Microsystems workstations and Postscript laser printers in their daily work. The group also has 3 Intel-based laptop computers. In the laboratory, mainly used by students in the different courses, there are a lot of different processes and some 10 Intel-based computers for measurement and control.

Comments and questions on the equipment can be directed to Patrik Lägermo.

The computer network consists of the following components.

- An Ethernet based 10baseT TCP/IP network
- 1 Sun SPARCsystem 300 server
- 1 Sun SPARCstation 1+
- 5 SPARCstation 2

- 5 SPARCstation ELC
- 19 SPARCstation SLC.
- 1 HP LaserJet 4Si MX (Ethernet connected) Postscript laser printer
- 1 QMS-PS 1700 Postscript laser printer
- 1 QMS-PS 810 Postscript laser printer
- 1 QMS-PS 800 Postscript laser printer

The Sun workstations run SunOS 4.1 and OpenWindows 3.0. X11R5 is also available. The software used in this network is mainly for advanced calculations and documenting. Among the mathematical programs are e.g. Matlab, Maple, Mathematica, Macsyma and Axiom. The system mainly used for preparing documents is TEXand LATEX. Accompanying programs such as xdvi, dvips and ghostview are also available. Write, Draw, Paint, Equation and Table from IslandGraphics, Inc., The Publisher from Arbor-Text, Inc. and FrameMaker from Frame Corporation are other document handling packages that the network offers. The public services available (e.g. anonymous ftp areas and mail server) are described in Section 2 of this report.

The laptop computers are:

- 1 Texas TravelMate 3000 WinSX
- 2 Texas TravelMate 4000 WinSLC

In the laboratory the following processes and computers are used:

- 11 AC and DC servo systems, Feedback MS150
- 5 hot air processes, Feedback PT326
- 9 simple tank processes
- 5 double tank processes

- 6 modular systems with simulated processes, PID-Lead/lag compensation, and time discrete controllers
- 1 air-driven generator plant
- 1 air-driven steam generator
- 1 hot water heating process
- 1 coupled tanks process, Tecquipment CE5
- 1 ball and beam process, Tecquipment CE6
- 1 ball and hoop process, Tecquipment CE9
- 1 coupled drives process, Tecquipment CE108
- 3 Lego processes for sequential control
- 1 helicopter-like process
- 2 wind meter processes from Chalmers Institute of Technology
- 8 LEO 386 computers with Metrabyte Dash 16 interfaces (A/D, D/A and digital I/O).
- 8 Ericsson AT computers
- 1 Compaq Deskpro 386 computer with the SattLine software.

Appendix D

Seminars

On finite memory estimation. Dr Alexander V Medvedev, Division of Automatic Control, LuleåUniversity of Technology, Luleå, Sweden, August 27, 1992.

Graphical modelling tools. Francis Lorenz, Lorenz Consulting, Belgium, September 17, 1992.

Quantitative design of a class of nonlinear systems with parameter uncertainty. Dr Per-Olof Gutman, Israel Institute of Technology, Haifa, Israel, September 24, 1992.

Discrete event systems and real world problems; a case study. Dr Silvano Balemi, ETH, Zurich, Switzerland, October 23, 1992.

Issues in force control of coordinated robots. Dr Stephen H Murphy, NASA Centre for Intelligent Robotic Systems for Space Exploration, RPI, Troy, NY, USA, November 23, 1992.

Some examples from ITM. Dr Uno Nävert, Institute of Applied Mathematics, Gothenburg, Sweden, November 26, 1992.

Maximum likelihood location estimation of wideband sources using the EM algorithm. Professor Johann F Böhme, Ruhr University, Bochum, Germany, December 8, 1992.

Neural networks in automation - fault diagnosis and control. Professor Heikki Koivo, Tampere University of Technology, Tampere, Finland, December 9, 1992.

Approximate ML frequency estimation. Professor Petre Stoica, Uppsala University, Uppsala, Sweden, December 9, 1992.

Design of discrete event systems by means of the boolean differential calculus. Dr Rainer Scheuring, Stuttgart University, Stuttgart, Germany, February 4, 1993.

On-line detection of abrupt changes. Dr Igor Nikiforov, Institute for Control Problems, Moscow, Russia, February 11, 1993.

Multivariate modelling, design and analysis in modern process industry Professor Svante Wold, Department of Chemistry, Umeå University, Umeå, Sweden, February 18, 1993.

STFI's work on modelling. Jan-Erik Gustafsson, STFI, Stockholm, Sweden, February 25, 1993.

Iterative identification and control design: The windsurfer approach. Dr Robert Kosut, Integrated systems Inc. Santa Clara, CA, USA, April 1, 1993.

Reachability tests for systems over polynomial rings using Gröbner bases. Luc Habets, Department of Mathematics and Computing Science, Eindhoven University of Technology, The Netherlands, April 22, 1993.

Logic control via COCOLOG Markovian fragments implemented by ATP: Foundations. Professor Peter Caines, McGill University, Montreal, Canada, April 27, 1993.

Logic control via COCOLOG Markovian fragments implemented by ATP: Overview and applications Professor Peter Caines, McGill University, Montreal, Canada April 29, 1993

On the genericity of stabilization for time-delay systems. Luc Habets, Department of Mathematics and Computing Science, Eindhoven University of

Technology, The Netherlands, April 29, 1993.

The algebraic approach to control systems design Professor Vladimir Kucera, Institute of Information Theory and Automation, Prague, Czeckia, May 10, 1993.

Perturbation analysis and discrete event systems: Part 1. Professor Christos Cassandras, University of Massachusetts at Amherst, USA, May 24, 1993.

Perturbation analysis and discrete event systems: Part 2. Professor Christos Cassandras, University of Massachusetts at Amherst, USA, May 25, 1993.

Control theory for partial differential equations and differential algebra. Professor J. F. Pommaret, Ecole des Ponts et Chausses, Paris, France, May 28, 1993.

Appendix E

Lectures by the staff

K. Forsman: *Symbolic Solution of Polynomial Systems with Applications to Nonlinear Control Systems*, Eindhoven Technical University, Dept. of Mathematics and Computing Science, Eindhoven, The Netherlands. July 2, 1992.

K. Forsman: *A Constructive Algebro-Geometric Framework for Nonlinear Control Theory*, Eindhoven Technical University, Dept. of Mathematics and Computing Science, Eindhoven, The Netherlands. July 8, 1992.

K. Forsman: *Nonlinear Discrete Time Systems - Some Questions of an Algebraic Nature*, University of Twente, Dept. of Applied Mathematics, Enschede, The Netherlands, July 14, 1992.

K. Forsman: *An Introduction to Gröbner Bases*, Dept. of Mathematics, University of Groningen, Groningen, The Netherlands. July 22, 1992.

J. Sjöberg: *Overtraining, Regularization, and Searching for Minimum in Neural Networks*. IFAC, ACASP, Grenoble, 1-3 July, 1992.

L. Ljung: *System Identification using Bond-Graphs*. IFAC Symposium on Adaptive Systems in Control and Signal Processing, Grenoble, France, July 1992.

L. Ljung: *A comment on "leakage" in Adaptive Algorithms*. 4th IFAC International Symposium on Adaptive Systems in Control and Signal Processing, Grenoble, France, July 1992.

H. Hjalmarsson: *Detection and Estimation of Non-Vanishing Model Errors*. California Institute of Technology, Pasadena, August 17, 1992.

K. Forsman: *An Introduction to Fuzzy Control for Control Theorists*, Saab Missiles, Linköping, Sweden. September 3, 1992.

K. Forsman: *Basics of Fuzzy Control*, Saab Military Aircraft Division, Linköping, Sweden. September 22, 1992.

F. Gustafsson: *Discrete parameters in linear systems* Science meeting, Saint Malo, September, 1992.

M. Viberg: *Array Processing Subject to Model Uncertainties: Optimal and Ad-Hoc Approaches*, Dept. of Elec. Comp. Eng., Brigham Young Univ., UT, USA, Sept. 1992.

L. Ljung: *Optimal and Ad Hoc Adaptation Mechanisms*. ISSSE'92, Paris, France, September 1992.

L. Ljung: *A System Identification Perspective on Neural Nets*. IEEE Workshop on Neural Networks for Signal Processing, Helsingör, Denmark, September 1992.

J. Sjöberg: *An Introduction to Artificial Neural Networks* SAAB-SCANIA Military Aircraft Division, Linköping, October, 1992.

M. Viberg: *Array Processing in Correlated Noise Fields Using Instrumental Variables and Subspace Fitting*, 26^{th} Asilomar Conf. Sig., Syst.,Comput., Monterey, CA, USA, Oct. 1992.

K. Forsman: *New Methods for Solving Nonlinear Equation Systems, with Applications to Control Theory*, Reglermöte '92, Chalmers Institute of Technology, Gothenburg, Sweden. November 4, 1992.

K. Forsman: *Fuzzy Control – a Short Introduction and Some Concrete Results*, Reglermöte '92, Chalmers Institute of Technology, Gothenburg, Sweden. November 4, 1992.

I. Klein: *Automatic Creation of Sequential Control Schemes*, Reglermöte '92, Chalmers Institute of Technology, Gothenburg, Sweden. November 4, 1992.

J.E. Strömberg: *Fuzzy Control – a Short Introduction and Some Concrete Results*, Reglermöte '92, Chalmers Institute of Technology, Gothenburg, Sweden. November 4, 1992.

T. Glad *Identifiability and differential algebra* Laboratoire des Signaux et Systemets, C.N.R.S.-E.S.E., Gif-sur-Yvette, France, November 25, 1992.

M. Viberg: *Array Processing Subject to Model Uncertainties: Optimal and Ad-Hoc Approaches*, Information Systems Lab, Stanford Univ., CA, USA, Nov. 1992.

L. Ljung: *Tracking Performance Analysis of the Forgetting Factor RLS Algorithm.* IEEE Conference on Decision and Control, Tucson, Arizona, USA, December 1992.

F. Gustafsson: *Time-Frequency Representations* Saab Military Aircraft Division, Link;ping, Sweden. January, 1993.

J.E. Strömberg: *Variable causality in bond graphs caused by discrete effects*, First Int. Conf. on Bond Graph Modeling, ICBGM '93, San Diego, United States, January 17, 1993.

J.E. Strömberg: *Bond graph supported estimation of discretely changing parameters*, First Int. Conf. on Bond Graph Modeling, ICBGM '93, San Diego, United States, January 17, 1993.

M. Viberg: *Maximum Likelihood and Subspace Based Approximations for Sensor Array Processing*, Information Systems Lab, Stanford Univ., CA, USA, Lecture series, Jan. 1993 – Feb. 1993.

F. Gustafsson: *Tire-Road Friction Estimation* Royal Institute of Technology, Stockholm, February, 1993.

S. Anderson: *Dimension Reduction in Array Processing* Yale University, New Haven, CT, USA, February 26, 1993.

T. Glad *Dynamic systems described by characteristic sets* Royal Institute of

Technology, Stockholm, March 19, 1993.

F. Gustafsson: *Friction Estimation in Cars* Institute of Information Theory and Automation, Prague, April, 1993.

P. Pucar: *Segmentation of Laser Range Images with Respect to Range and Variance* SPIE Conference, Orlando, April, 1993.

M. Viberg: *Subspace Methods for Array Processing and System Identification*, Information Systems Lab, Stanford Univ., CA, USA, Apr. 1993.

L. Ljung: *Frequency Domain Techniques in System Identification.* Workshops on Adaptive and Fuzzy Control, IMA, Minneapolis, USA, April 15, 1993.

H. Hjalmarsson *Model quality issues in system identification*, Chalmers Institute of Technology, Gothenburg, Sweden, May 1993.

R. Germundsson: *Symbolic and Algebraic Methods for Modeling, Analysis, Design and Implementation of Discrete Systems* Workshop on Complex Systems, ITM '93, KTH, Stockholm, Sweden, May 14, 1993.

J.E. Strömberg: *Modular Modelling with Bond Graphs*, Workshop on Complex Systems, ITM '93, KTH, Stockholm, Sweden, May 14, 1993.

M. Viberg: *Analysis of the Combined Effects of Finite Samples and Model Errors on Array Processing Performance*, ICASSP 93 Conference, Minneapolis, MN, May 1993.

K. Forsman: *Some Generic Results on Algebraic Observability and Connections with Realization Theory*, ECC '93, Groningen, The Netherlands, June 30, 1993.

J.E. Strömberg: *Modelling mode switching in dynamic systems*, European Control Conference, ECC '93, Groningen, The Netherlands, June 30, 1993.

J. Sjöberg: *Artificial Neural Networks and System Identification*, Ericsson Radio Systems AB, Linköping, June, 1993.

T. Glad: *An algebraic approach to linear and nonlinear control*, (with M. Fliess), European Control Conference (ECC'93), Groningen, The Netherlands, June 29, 1993.

T. Glad: *Identifiability implies robust identifiability*, European Control Conference, (ECC'93), Groningen, the Netherlands, JUne 30, 1993.

H. Hjalmarsson: *Optimality and robustness in parameter estimation*, The Royal Institute of Technology, Stockholm, Sweden, June 1993.

L. Ljung: *Modelling of Industrial Systems.* Symposium ISMIS'93, Trondheim, Norway, June 1993.

Appendix F

Travel and Conferences

Lennart Ljung participated in the IFAC Symposium on Adaptive Systems and Control and Signal Processing in Grenoble, July 1992. He then participated in the IEEE Workshop for Neural Networks and Signal Processing in Helsingör, August, September 1992 and also in the URSI Meeting in Paris, September 2-4. He took part in the European Network (SCIENCE) on Identification meeting, September 28-30 in 1992 and also in the Swedish Reglermöte'92 in Gothenburg, November 3-5. He participated in the Conference on Decision and Control in Tucson, December 15-18. April 12-20 he spent with the Institute of Mathematics and its Applications in Minneapolis for the Workshops on Adaptive Control and on Fuzzy Control. Furthermore he participated in the IFAC Presidents' Meeting in Laxenburg, May 5-8. On June 14 he was a member of a jury of a thesis in Grenoble and June 15-17 he participated in the ISMIS Meeting in Trondheim.

Torkel Glad visited Laboratoire des Signaux et Systemets, C.N.R.S.-E.S.E., Gif-sur-Yvette, France, November 23–28, 1992 and the European Control Conference (ECC '93), Groningen, The Netherlands on June 28 – July 1, 1993.

Mille Millnert participated in SPIE's OE/Aerospace and Remote Sensing - 1993 International Symposium and Exhibition on OPtical Engineering and Photonics in Aerospace and Remote Sensing, 12-16 April, 1993, Orlando, Florida, USA. June 1-2 he attended the Workshop for the NUTEK "Digital

Kommunikation" frame program in Stockholm.

Svante Gunnarsson participated in the Science Workshop on System Identification, St Malo, France 28–30 September, Education Day at Chalmers University of Technology, Göteborg, November 3, Third Scandinavian International Conference on Fluid Power, Linköping, May 25–26, and the European Control Conference , Groningen, The Netherlands, June 28 – July 1. On March 11 he visited Nynäs Petroleum in Stockholm.

Mats Viberg visited the Department of Electrical and Computer Engineering at Brigham Young University, Utah, USA, during August and September 1992. From October 1992 until August 1993 he was a Post-doc at Information Systems Lab, Stanford University, California, USA. During October 30 until November 2, 1992, he attended the 26th Asilomar Conference on Signals, Systems and Computers, Monterey, USA and April 27-30 he participated in ICASSP '93, Minneapolis, USA.

Alf Isaksson participated in the Conference Control Systems'92 on Process Control in the Pulp and Paper Industry which was held in Whistler, Canada, September 29-October 1, 1992. In conjunction with that he also visited Pulp and Paper Research Centre at University of British Columbia, October 2, 1992. Furthermore he attended the Reglermöte '92, Chalmers Institute of Technology, Gothenburg, Sweden, November 4, 1992. He also participated in Tooldiag '93 in Toulouse, France, April 5-7, 1993 and the European Control Conference in Groningen, The Netherlands, June 28 - JUly 1, 1993.

Jan-Erik Strömberg attended the Reglermöte'92, Chalmers Institute of Technology, Gothenburg, Sweden, November 4, 1992, the First Int. Conf. on Bond Graph Modelling, ICBGM'93, San Diego. United States, January 17, 1993, the Workshop on Complex Systems, ITM'93, KTH, Stockholm, Sweden, May 14, 1993, and the European Control Conference, ECC'93, Groningen, The Netherlands, June 30, 1993.

Inger Klein attended the "Reglermöte '92" in Gothenburg, Sweden, November 1992.

Peter Lindskog attended the "Reglermöte '92" in Gothenburg, Sweden, November 1992.

Roger Germundsson attended the WODES'92 workshop on discrete events in

Prague, Czechia in August '92. He also attended the *Mathematica* conference in Rotterdam, the Netherlands, August 1993. Over the year he also visited Ericsson Telecom on several occasions. Finally he participated in a workshop on complex systems organized by ITM at the Royal Institute of Technology, Stockholm, Sweden, in May 1993.

Krister Forsman visited the universities of Eindhoven, Twente and Groningen (The Netherlands) during July 1992, invited by the Dutch Systems Theory Network. He participated in the "Reglermöte" in Gothenburg in November 1992. He also participated in the 2nd ECC in Groningen, The Netherlands in June 1993.

Sören Andersson attended the International Conference on Acoustics, Speech and Signal Processing in Minneapolis, USA, April 27–30, 1993. Since February 1, 1993, he is a Postdoctoral Associate at the Department of Electrical Engineering, Yale University, New Haven, USA.

Håkan Hjalmarsson attended the Swedish Automatic Control Meeting in Gothenburg, Sweden, November 4-5, 1992.

Fredrik Gustafsson attended the 4th IFAC Symposium ACASP in Grenoble 1–3 July, 1992. He participated in the Science meeting in San Malo, September 29–30, 1992. For the Swedish Prometheus project DALTM, he visited AB Volvo eight times and Porsche on March 18, 1993. He also spent two days on the test track in Arvidsjaur, March 30–31, 1993. He attended the Swedish Automatic Control Meeting in Gothenburg, Sweden, November 1992.

Jonas Sjöberg participated in the 4th IFAC Symposium on Adaptive Systems in Control and Signal Processing in Grenoble 1-3, 1993. September 28–30 he participated in The Science Workshop on Identification in Saint Malo, France. In March he visited the Systems Control Group at Uppsala University and in May the Control Group of KTH, Stockholm. In May he visited ABB Kraftwerk in Baden, Switzerland and in June 1993 he participated in the course "From Statistics to Neural Networks" given by NATO Advanced Study Institute, Les Arcs, France.

Predrag Pucar participated in the First Workshop of the Science Project on System Identification, organized by the European Research Network on System Identification, in Saint Malo, France, September 28–30, 1992. He attended the conference "Reglermöte '92" in Gothenburg, Sweden, November

4-5, 1992. He participated in SPIE's OE/Aerospace and Remote Sensing - 1993 International Symposium and Exhibition on Optical Engineering and Photonics in Aerospace and Remote Sensing, 12-16 April 1993, Orlando, Florida USA. June 1-2 he attended the Workshop for the NUTEK "Digital Kommunikation" frame program in Stockholm, Sweden.

Torbjörn Andersson participated in the First Workshop of the Science Project on System Identification, organized by the European Research Network in Saint Malo, France, September 28–30, 1992. He also attended "Reglermöte '92" in Gothenburg, Sweden, November 4–5, 1992.

Tomas McKelvey participated in the Science Workshop on System Identification in Saint Malo, France, September 28-30, 1992.

Jonas Plantin participated in the second Baltic Olympiad on Automatic Control in St Petersburg, Russia, September 23–25, 1992.

Anders Ericsson participated in the second Baltic Olympiad on Automatic Control in St Petersburg, Russia, September 23–25, 1992.

Ingegerd Stenlund and Ulla Salaneck participated in the secretaries' program at the Reglermöte'92 in Göteborg in November 1992 and visited the IFAC Secretariat in May 1993.

Appendix G

Publications

Ph.D. Theses

[1] T. Svensson, *Mathematical Tools and Software for Analysis and Design of Nonlinear Control Systems*, PhD thesis, Linköping University, Linköping, Sweden, 1992, Linköping Studies in Science and Technology, Dissertations No. 285.

Abstract

The theory of nonlinear control systems has developed rapidly during the last decades, but still only small parts of this theory have become standard tools for a control engineer in practice. There are at least two reasons for this. One is that the theory still lacks many results related to practical issues, such as constructive computational methods and robustness results. The other reason is that there are few software tools available to support the new theory.

In this thesis we will give a survey of some mathematical tools, in which we focus on constructive theory. In particular we will describe the theory of Volterra series and exact linearization in detail, since we believe that these theories have the potential to become standard mathematical tools in control theory.

With this theory as a background, we then study some issues of practical importance. We investigate structural questions for Volterra series and derive some results on complexity and computational aspects. The use of a reduced Kronecker product formalism is pointed out, and an attempt to connect the input-output behavior of a nonlinear system and the controller design is made.

Then, we investigate some robustness issues arising when exact linearization is used as a design method. We study the robustness properties of an LQ design and show how Volterra series descriptions can be used to analyze the effect of model errors.

In order to make the theory useful and available for the user in a more practical situation, some algorithms for nonlinear computations are presented and a software package for computer algebra systems is developed. Examples and implementations are made in two such systems, and some aspects of using them are given.

[2] S. Andersson, *On Dimension Reduction in Sensor Array Signal Processing*, PhD thesis, Linköping University, Linköping, Sweden, 1992, Linköping Studies in Science and Technology, Dissertations No. 290.

Abstract

During the last decades, sensor array signal processing has been a very active research area. More recently, relations between many of the proposed methods has been examined. The problem of assessing the estimation accuracy of these methods has also been addressed. Real-world applications of these techniques involves spatial distribution of several sensors to be used for collecting measurements of interesting emitted waveforms. From the measurements, detection and localization as well as estimation of the emitted waveforms can be accomplished. Common examples of applications are radar (electromagnetic waveforms) and sonar (acoustical underwater waveforms).

Another aspect of array processing that recently has been addressed in the literature is that of dimension reduction, where the data vectors collected at the sensor outputs are reduced in size. This reduction is employed mainly in order to lower the amount of computations necessary for obtaining the parameter-estimates of interest; but some other improvements has also been observed. These include, *e.g.*, lower sensitivity to sensor noise correlations and, for some estimation methods, higher resolution capability.

In this thesis, it is demonstrated how to make the dimension reduction in an optimal fashion, where the optimality is with respect to estimation accuracy. More precisely, an expression to be satisfied by a transformation matrix acting on the sensor outputs is derived, that preserves the optimally achievable estimation accuracy (the Cramér-Rao bound) also in the reduced space. A transformation matrix design method that tries to reduce some unwanted properties of the optimal transformation is also outlined and examined. This method is based on numerical optimization of a particular performance measure, motivated by the insight obtained in the process of finding the optimal transformation.

Moreover, an asymptotic analysis is performed, using the reduced data vectors, that examines the estimation accuracy of several estimation methods when a large number of sensor elements is used. This analysis is valid for a fairly general transformation matrix, and the methods considered are the Weighted Subspace Fitting (WSF) and Noise Subspace Fitting (NSF) methods, including MUSIC. By employing the optimal transformation matrix, the WSF method is shown to to be efficient, *i.e.*, to attain the Cramér-Rao bound. An examination of the estimation accuracy, compared to that optimally attainable, is made for the case when the transformation matrix differs from the optimal one.

Finally, an application is studied, considering the potential use of sensor arrays in mobile communication systems.

[3] H. Hjalmarsson, *Aspects in Incomplete Modeling in System Identification*, PhD thesis, Linköping University, Linköping, Sweden, 1993, Linköping Studies in Science and Technology, Dissertations No. 298.

Abstract

This thesis considers several aspects of the system identification problem. The major issues, however, are how one should represent and assess model errors. These issues have come to be central in system identification in recent years – mainly due to their relevance for robust control.

The *random error* is the deviation between models based on finite data and infinite data. A measure of this error is the covariance matrix of the parameter estimate. An explicit expression for this covariance matrix has been known for long but, except under very restrictive assumptions, a consistent estimate has been missing. We derive two, conceptually different, simple, explicit and consistent estimation methods.

A somewhat controversial issue in identification is whether disturbances should be considered as deterministic or stochastic. We show that, for prediction error methods or correlation methods, the input can be used to force a deterministic disturbance to behave like a stochastic disturbance from an identification point of view.

Current model error problem formulations are somewhat ill-defined; it is in principle always possible to estimate the system perfectly asymp-

totically. We analyze a, perhaps more realistic, problem formulation which prevents this from being possible.

When experimental data is sparse it is important to be able to incorporate prior knowledge of the system. A Bayesian procedure, suitable for transfer function estimation, is developed for this purpose.

Model validation is another important issue. A standard procedure is to use statistical so called correlation tests. Previously it has been noticed that these tests may give levels of significance that differ from the desired ones. We show that it is possible to modify these tests so as to avoid this artifact.

Spectral analysis is widely used for identification and time-series analysis. The method has previously been thoroughly analyzed from a quadratic mean point of view and here we complement this analysis with an almost sure convergence analysis.

To support the analysis of the aforementioned methods a stochastic framework is developed. Byproducts of this are extensions of some convergence results for prediction error methods and instrumental variable methods.

[4] I. Klein, *Automatic Synthesis of Sequential Control Schemes*, PhD thesis, Linköping University, Linköping, Sweden, 1993, Linköping Studies in Science and Technology, Dissertations No. 305.

Abstract

Of all hard- and software developed for industrial control purposes, the majority is devoted to sequential, or binary valued, control and only a minor part to classical linear control. Typically, the sequential parts of the controller are invoked during startup and shut-down to bring the system into its normal operating region and into some safe standby region, respectively. Despite its importance, fairly little theoretical research has been devoted to this area, and sequential control programs are therefore still created manually without much theoretical support to obtain a systematic approach.

We propose a method to create sequential control programs automatically. The main idea is to spend some effort off-line *modelling* the plant, and from this model generate the control strategy, that is the *plan*. The plant is modelled using *action structures*, thereby concentrating on the actions instead of the states of the plant. In general the planning problem shows exponential complexity in the number of state variables.

However, by focusing on the actions, we can identify problem classes as well as algorithms such that the planning complexity is reduced to polynomial complexity. We prove that these algorithms are *sound*, i.e., the generated solution will solve the stated problem, and *complete*, i.e., if the algorithms fail, then no solution exists. The algorithms generate a plan as a set of actions and a partial order on this set specifying the execution order. The generated plan is proven to be minimal and maximally parallel.

For a larger class of problems we propose a method to split the original problem into a number of simpler problems that can each be solved using one of the presented algorithms. It is also shown how a plan can be translated into a GRAFCET chart, and to illustrate these ideas we have implemented a planning tool, i.e., a system that is able to automatically create control schemes. Such a tool can of course also be used on-line if it is fast enough. This possibility opens up completely new applications such as operator supervision and simplified error recovery and restart procedures after a plant fault has occurred.

Additionally we analyze reachability for a restricted class of problems. For this class we state a reachability criterion that may be checked using a slightly modified version of one of the above mentioned algorithms.

Licentiate Thesis

[5] J. Sjöberg, *Regularization Issues in Neural Network Models of Dynamical Systems*, Linköping studies in science and technology. Thesis no.366, LiU-Tek-Lic-1993:08, ISBN 91-7871-072-3, ISSN 0280-7971, Department of Electrical Engineering, Linköping University, Sweden, February 1993.

Abstract

The latest era of neural networks started some ten years ago and the literature has been characterized by many successful applications, but the underlying theory is often omitted. In this thesis *feed-forward* neural networks are considered from a system identification point of view. Two nonlinear generalizations of the linear ARX and OE models are investigated and theoretically justified.

Neural networks are often characterized by the fact that they use a fairly large amount of parameters. We address the problem how this can be done without the usual penalty in terms of a large variance error. We show that *regularization* is a key explanation, and that terminating a gradient search ("backpropagation") before the true criterion minimum is found is a way of achieving regularization. This theory also explains the concept of "overtraining" in neural nets.

Journal Papers

[6] S. Andersson, "On Optimal Dimension Reduction for Sensor Array Signal Processing", *Signal Processing, Elsevier Science Publishers*, **30**(2), Jan. 1993.

[7] B. Wahlberg and L. Ljung, Hard frequency-domain model error bounds from least-squares like identification techniques, *IEEE Transactions on Automatic Control*, **AC-37**:900–912, 1992.

[8] H. Hjalmarsson and L. Ljung, "Estimating Model Variance in the Case of Undermodelling", *IEEE Trans. Automatic Control*, **37**:1004–1008, July 1992.

[9] B. Ottersten, M. Viberg, P. Stoica, and A. Nehorai, Exact and large sample ML techniques for parameter estimation and detection in array processing, *Radar Array Signal Processing*, 1992.

[10] A. Babić, E. Krusinska, and J.-E. Strömberg, Extraction of diagnostic rules using recursive partitioning systems: A comparision of two approaches, *Artificial Intelligence in Medicine*, **4**:373–387, 1992.

[11] L. Ljung, A discussion of model accuracy in system identification, *Int. Journal of Adaptive Control and Signal Processing*, **6**(3):161–171, 1992.

[12] L. Ljung, O tochnosti modeli v identifikatsii sistem, *Tekhicheskaya Kibernetika*, **6**:55–64, 1992.

[13] D. Letalick, M. Millnert, and I. Renhorn, Terrain segmentation using laser radar range data, *Applied Optics*, **31**(15):2883–2890, 1992.

[14] S. Gunnarsson, "On some asymptotic uncertainty bounds in recursive least squares identification", *IEEE Transactions on Automatic Control*, 1993.

[15] L. Ljung, Identification of linear systems, In D. A. Linkens, editor, *CAD for Control Systems*, pages 147–165. Marcel Dekker, New York, 1993.

[16] B. Wahlberg, L. Ljung, and T. Söderström, On sampling of continuous time stochastic processes, *Control-Theory and Advanced Technology*, **9**(1):99–113, 1993.

[17] B. Ottersten, M. Viberg, P. Stoica, and A. Nehorai, Exact and large sample ML techniques for parameter estimation and detection in array processing, In Haykin, Litva, and Shepherd, editors, *Radar Array Processing*, pages 99–151. Springer-Verlag, Berlin, 1993.

[18] H. Akçay and H. Hjalmarsson, Trade-offs in least-squares identification for FIR systems subject to worst-case noise, *Systems and Control Letters*, To appear.

[19] L. Guo, L. Ljung, and P. Priouret, Performance analysis of the forgetting factor RLS algorithms, *Int. Journal of Adaptive Control and Signal Processing*, 1993, To appear.

[20] L. Ljung and T. Glad, On global identifiability of arbitrary model parameterizations, *Automatica*, February 1994.

[21] P. Stoica, M. Viberg, and B. Ottersten, Instrumental variable approach to array processing in spatially correlated noise fields, *IEEE Transactions on Signal Processing*, January 1994.

Conference Papers

[22] F. Gustafsson, A two-filter approach to optimal detection of jumps in linear systems, In *4th IFAC Symposium on Adaptive Systems in Control and Signal Processing*, pages 681–686, Grenoble, France, 1-3 July 1992.

[23] F. Gustafsson and B. Wahlberg, On simultaneous system and input sequence estimation, In *4th IFAC Symposium on Adaptive Systems in Control and Signal Processing*, pages 93–98, Grenoble, France, 1-3 July 1992.

[24] B. Ottersten, M. Viberg, and B. Wahlberg, "Source Localization in the Presence of Model Uncertainties", In *Proc. Adaptive Algorithms in Comm. Conf. 92*, Bordeaux, France, Oct. 1992.

[25] M. Viberg, P. Stoica, and B. Ottersten, "Array Processing in Correlated Noise Fields Using Instrumental Variables and Subspace Fitting", In *Proc.* 26^{th} *Asilomar Conf. Sig., Syst.,Comput.*, Oct. 1992.

[26] S. T. Glad, Nonlinear input output relations and identifiability, In *Proc. 31st IEEE Conference on Decision and Control*, Tucson, Arizona, December 1992.

[27] M. Viberg and L. Swindlehurst, "Analysis of the Combined Effects of Finite Samples and Model Errors on Array Processing Performance", In *Proc. ICASSP 93 Conf.*, Minneapolis, MN, April 1993.

[28] L. Swindlehurst and M. Viberg, Efficient Subspace Fitting Algorithms for Diversely Polarized Arrays, In *Proc. ICASSP 93 Conf.*, Minneapolis, MN, April 1993.

[29] K. Forsman and J-E Strömberg, Fuzzy control – a short introduction and some concrete results, In *Proc. Reglermöte '92*, Gothenburg, November 1992, (In Swedish).

[30] K. Forsman, New methods for solving nonlinear equation systems, with applications to control theory, In *Proc. Reglermöte '92*, Gothenburg, November 1992, (In Swedish).

[31] P. Pucar, M. Millnert, D. Letalick, and I. Renhorn, Segmentation of range images with respect to range and variance, Orlando, FL, USA, April 1993. Signal Processing, Sensor Fusion and Target Recognition II. OE/Aerospace sensing, Proc. SPIE Vol. 1955, pp 195-207.

[32] P. Krus and S. Gunnarsson, "Adaptive control of a hydraulic crane using on-line identification", In *Prepr. The Third Scandinavian International Conference on Fluid Power*, volume 2, pages 363–388, Linköping, Sweden, 1993.

[33] J. Sjöberg and L. Ljung, Overtraining, regularization and searching for minimum in neural networks, In *4th IFAC International Symposium on Adaptive Systems in Control and Signal Processing, ACASP/92*, pages 669–674, Grenoble, France, July 1992.

[34] P. A. J. Nagy and L. Ljung, System identification using bond-graphs, In *Proc. IFAC Symposium on Adaptive Systems in Control and Signal Processing*, pages 415–420, Grenoble, France, July 1992.

[35] B. Egardt, C. R. Johnson, L. Ljung, and G. A. Williamsson, Adaptive system performance in the frequency domain, In *Proc. IFAC Symposium on Adaptive Systems in Control and Signal Processing*, pages 33–40, Grenoble, France, July 1992.

[36] L. Ljung and J. Sjöberg, A comment on "leakage" in adaptive algorithms, In *4th IFAC International Symposium on Adaptive Systems in Control and Signal Processing, ACASP/92*, pages 377–382, Grenoble, France, July 1992.

[37] J.-E. Strömberg, J. Top, and U. Söderman, Variable causality in bond graphs caused by discrete effects, In *Proc. First Int. Conf. on Bond Graph Modeling (ICBGM '93)*, number 2 in SCS Simulation Series, volume 25, pages 115–119, San Diego, 1993.

[38] J.-E. Strömberg, U. Söderman, and J. Top, Bond graph supported estimation of discretely changing parameters, In *Proc. First Int. Conf. on Bond Graph Modeling (ICBGM '93)*, number 2 in SCS Simulation Series, volume 25, pages 47–52, San Diego, 1993.

[39] L. Guo, L. Ljung, and P. Priouret, Tracking performance analysis of the forgetting factor rls algorithm, In *IEEE Conference on Decision and Control*, Tucson, Arizona, December 1992.

[40] L. Ljung, Optimal and ad hoc adaptation mechanisms, In *ISSSE '92*, Paris, France, September 1992.

[41] L. Ljung, Modelling of industrial systems, In J. Komorowski and Z. W. Ras, editors, *Methodologies for Intelligent Systems*, pages 338–350, Trondheim, Norway, June 1993. 7th Int. Symposium, ISMIS'93, Springer Verlag.

[42] L. Ljung and J. Sjöberg, A system identification perspective on neural nets, In S. Y. Kung, editor, *IEEE Workshop on Neural Networks for Signal Procesing*, 445 Hoes Lane, Piscataway, NJ, September 1992. IEEE Science Center.

[43] M. Fliess and S. T. Glad, An algebraic approach to linear and nonlinear control, In H. L. Trentelman and J. C. Willems, editors, *Essays on control: Perspectives in the theory and its applications*, pages 223–267. Birkhäuser, 1993.

[44] H. Hjalmarsson, Non-vanishing model errors, In R. Smith, editor, *Workshop on the Modeling of Uncertainty in Control Systems*. Springer-Verlag, 1993.

[45] K. Forsman, Some generic results on algebraic observability and connections with realization theory, In J. W. Nieuwenhuis, C. Praagman,

and H. L. Trentelman, editors, *Proc. 2nd European Control Conference*, pages 1185–1190, Groningen, July 1993, Volume 3.

[46] L. Ljung, T. Glad, and T. Andersson, Identifiability implies robust identifiability, In J. W. Nieuwenhuis, C. Praagman, and H. L. Trentelman, editors, *Proc. 2nd European Control Confernce*, pages 2144–2148, Groningen, July 1993, Volume 4.

[47] J.-E. Strömberg, J. Top, and U. Söderman, Modelling model switching dynamic systems, In *Proc. Second European Control Conference (ECC'93)*, pages 848–853, Groningen, July 1993, Volume 2.

[48] S. Gunnarsson and P. Krus, LQG control of a hydraulic actuator with a flexible mechanical load, In *Proc. 12th IFAC World Congress*, pages VI–223, Sydney, Australia, July 1993.

[49] J. Sjöberg, T. McKelvey, and L. Ljung, On the use of regularization in system identification, In *Preprint 12th IFAC World Congress*, pages 381–386, Sydney, Australia, July 1993, Volume 7.

[50] F. Gustafsson and H. Hjalmarsson, Nineteen ML estimators for model structure selection, In *Proc. 12th IFAC World Congress*, pages VII–119, Sydney, Australia, July 1993.

[51] F. Gustafsson and B. Wahlberg, Identifiability in blind equalization, In *Proc. 12th IFAC World Congress*, pages VII–125, Sydney, Australia, July 1993.

[52] A. Isaksson and F. Gustafsson, A Bayesian approach to manoeuvre tracking and detection, In *Proc. 12th IFAC World Congress*, pages II–167, Sydney, Australia, July 1993.

[53] F. Gustafsson, On the estimation of discrete parameters in linear systems, In *Proc. 12th IFAC World Congress*, page 351, Sydney, Australia, July 1993, Volume 7.

[54] M. Viberg, L. Ljung, B. Ottersten, and B. Wahlberg, Performance of subspace based state-space, In *Proc. 12th IFAC World Congress*, page 369, Sydney, Australia, July 1993, Volume 7.

[55] L. Ljung, The process of identification, In *Proc. 12th IFAC World Congress*, page 197, Sydney, Australia, July 1993, Volume 5.

[56] H. Hjalmarsson, A model variance estimator, In *Proc. 12th IFAC World Congress*, pages IX–5, Sydney, Australia, July 1993.

[57] H. Hjalmarsson, Detecting asymptotically non-vanishing model uncertainty, In *Proc. 12th IFAC World Congress*, pages V–63, Sydney, Australia, July 1993.

Appendix H

Technical Reports

[58] J.-E. Strömberg, J. Top, and U. Söderman, Variable causality in bond graphs caused by discrete effects, Technical Report LiTH-I-ISY-1375, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[59] J.-E. Strömberg, U. Söderman, and J. Top, Bond graph supported estimation of discretely changing parameters, Technical Report LiTH-I-ISY-1376, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[60] J.-E. Strömberg, A. J. Isaksson, and L. Ljung, Towards online tree construction, Technical Report LiTH-I-ISY-1377, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[61] L. Ljung, J. Sjöberg, and T. McKelvey, On the use of regularization in system identification, Technical Report LiTH-I-ISY-1379, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[62] R. Germundsson, The local guide to fonts in $\TeX$, Technical Report LiTH-I-ISY-1380, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[63] S. Andersson, Beamspace transformation matrix design using numerical optimization, Technical Report LiTH-I-ISY-1383, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[64] S. Andersson, Asymptotic analysis of subspace methods for beamspace direction-of-arrival estimation using large arrays, Technical Report LiTH-I-ISY-1384, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[65] S. Andersson, On two-stage schemes for beamspace direction-of-arrival estimation, Technical Report LiTH-I-ISY-1385, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[66] K. Forsman, POLYCON - a Maple package for polynomial and rational control systems, Technical Report LiTH-I-ISY-1386, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[67] T. Svensson, A computer algebra toolbox for nonlinear control systems, Technical Report LiTH-I-ISY-1390, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[68] K. Forsman, Two themes in commutative algebra: Algebraic dependence and Kähler differentials, Technical Report LiTH-I-ISY-1392, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[69] L. Guo, L. Ljung, and P. Priouret, Tracking performance analysis of the forgetting factor RLS algorithm, Technical Report LiTH-I-ISY-1393, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[70] A. J Isaksson and F. Gustafsson, A bayesian approach to manoeuvre tracking and detection, Technical Report LiTH-I-ISY-1394, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[71] K. Forsman, Elementary aspects of constructive commutative algebra, Technical Report LiTH-I-ISY-1395, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[72] F. Gustafsson and B. Wahlberg, Identifiability in blind equalization, Technical Report LiTH-I-ISY-1397, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[73] F. Gustafsson and H. Hjalmarsson, Seventeen ML estimators for model structure selection, Technical Report LiTH-I-ISY-1398, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[74] F. Gustafsson, Estimation of discrete parameters in linear systems, Technical Report LiTH-I-ISY-1399, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[75] P. Lindskog, GRAFCET-TOOL - a grafcet imiplementation in G2, Technical Report LiTH-I-ISY-1402, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[76] K. Forsman, Some generic results on algebraic observability and connections with realization theory, Technical Report LiTH-I-ISY-1403, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992, In proceedings of ECC '93, Groningen.

[77] F. Gustafsson, Q. Zhang, and L. Ljung, On the estimation of tire-road friction, Technical Report LiTH-I-ISY-1405, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[78] F. Gustafsson, Estimation of discrete parameters in linear systems, Technical Report LiTH-I-ISY-1406, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[79] H. Fortell, Modellering av träpanna, Technical Report LiTH-I-ISY-1407, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[80] H. Hjalmarsson, Asymptotic relations between non-weighted and exponentially weighted series: A functional limit approach, Technical Report LiTH-I-ISY-1411, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[81] H. Hjalmarsson and F. Gustafsson, Transfer function estimation: A multiple model based Bayesian approach, Technical Report LiTH-I-ISY-1412, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[82] H. Hjalmarsson, A model variance estimator, Technical Report LiTH-I-ISY-1413, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[83] H. Hjalmarsson, Model variance estimation, Technical Report LiTH-I-ISY-1414, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[84] H. Hjalmarsson, Detecting asymptotically non-vanishing model uncertainty, Technical Report LiTH-I-ISY-1415, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[85] H. Hjalmarsson, Non-vanishing model errors, Technical Report LiTH-I-ISY-1416, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[86] H. Hjalmarsson, Assessing model uncertainty in terms of time-variations, Technical Report LiTH-I-ISY-1417, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[87] H. Hjalmarsson and L. Ljung, Estimating model variance in the case of undermodeling, Technical Report LiTH-I-ISY-1418, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[88] H. Hjalmarsson, Some reflections on control design based on experimental data, Technical Report LiTH-I-ISY-1419, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[89] H. Hjalmarsson, An invariance principle for "reverse" mixingales, Technical Report LiTH-I-ISY-1420, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[90] A. J. Isaksson, Estimation of average residence time given an identified AR-model, Technical Report LiTH-I-ISY-1422, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[91] Q. Zhang, Wavelet network: The radial structure and an efficient initialization procedure, Technical Report LiTH-I-ISY-1423, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[92] U. Söderman, J. Top, and J.-E. Strömberg, Modelling physical systems with changing structure, Technical Report LiTH-I-ISY-1428, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[93] Inger K. and P. Lindskog, Automatic creation of sequential control schemes in polynomial time, Technical Report LiTH-I-ISY-1430, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[94] K. J. Åström, A. Benveniste, P. E. Caines, G. Cohen, and L. Ljung, Facing the challenge of computer science in the industrial applications of control, Technical Report LiTH-I-ISY-1432, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[95] L. Guo, L. Ljung, and P. Priouret, Performance analysis of forgetting factor RLS, Technical Report LiTH-I-ISY-1433, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[96] I. Klein, Reachability for a class of sequential control problems, Technical Report LiTH-I-ISY-1434, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[97] J.-E. Strömberg, J. Top, and U. Söderman, Modelling model switching in dynamical systems, Technical Report LiTH-I-ISY-1435, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[98] K. Forsman, Localization and base change techniques in computational algebra, Technical Report LiTH-R-ISY-1445, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[99] K. Forsman, POLYCON - Computer algebra software for polynomial control systems, Technical Report LiTH-R-ISY-1447, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[100] M. Viberg, P. Stoica, and B. Ottersten, Array processing in correlated noise fields using instrumental variables and subspace fitting, Technical Report LiTH-R-ISY-1450, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[101] M. Viberg and A. Swindlehurst, Analysis of the combined effects of finite samples and model errors on array processing performance, Technical Report LiTH-R-ISY-1451, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[102] K. Forsman, A. Stenman, and J.-E. Strömberg, FuzzyCAT - towards a mathematical analysis of fuzzy controllers, Technical Report LiTH-R-ISY-1452, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[103] P. Pucar, M. Millnert, I. Renhorn, and D. Letalick, Segmentation of laser range images with respect to range and variance, Technical Report LiTH-R-ISY-1453, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[104] T. McKelvey, System identification using overparameterized state-space models, Technical Report LiTH-R-ISY-1454, Dept of EE Linköping University, S-581 83 Linköping, Sweden, 1993.

[105] K. Forsman and J. Eriksson, Solving the ARE symbolically, Technical Report LiTH-R-ISY-1456, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[106] L. Ljung, Modelling of industrial systems, Technical Report LiTH-R-ISY-1457, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[107] K. Forsman, Some generic results on algebraic observability and connections with realization theory, Technical Report LiTH-R-ISY-1458, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[108] M. Viberg, B. Ottersten, B. Wahlberg, and L Ljung, Performance of subspace based state-space system identification methods, Technical Report LiTH-R-ISY-1459, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[109] T. Andersson and P. Pucar, Estimation of residence time in continuous flow systems with varying flow and volume, Technical Report LiTH-R-ISY-1460:93, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[110] F. Gustafsson and H. Hjalmarsson, Nineteen ML estimators for model structure selection, Technical Report LiTH-R-ISY-1462, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[111] F. Gustafsson, On the estimation of discrete parameters in linear systems, Technical Report LiTH-R-ISY-1463, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[112] L. Ljung, T. Glad, and T. Andersson, Identifiability implies robust identifiability, Technical Report LiTH-R-ISY-1466, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[113] K. Forsman, Optimization, stability and cylindrical decomposition, Technical Report LiTH-R-ISY-1472, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[114] S. Nadjm-Tehrani and J.-E. Strömberg, Compositional modelling of hybrid systems, Technical Report LiTH-R-ISY-1474, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[115] A. Swindlehurst and M. Viberg, Subspace fitting with diversely polarized antenna arrays, Technical Report LiTH-R-ISY-1475, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[116] F. Gustafsson and H. Ekström, Tire – road friction estimation results from field trials in Arvidsjaur, Technical Report LiTH-R-ISY-1476, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[117] R. Germundsson, Symbolic and algebraic methods, analysis, design and implementation of discrete systems, Technical Report LiTH-R-ISY-1477, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[118] H. Akcay and H. Hjalmarsson, The least-squares identification of FIR systems subject to worst-case noise, Technical Report LiTH-R-ISY-1479, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[119] H. Ekström and F. Gustafsson, Hardware and software documentation for tire-road friction estimator, Technical Report LiTH-R-ISY-1480, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[120] Projects in system identification, Technical Report LiTH-R-ISY-1481, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[121] K. Forsman and A. Stenman, Fuzzycat - a fuzzy control analysis tool for maple, Technical Report LiTH-R-ISY-1487, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[122] T. Henriksson, M. Pettersson, and F. Gustafsson, An investigation of the longitudinal dynamics of a car, especially air drag and rolling resistance, Technical Report LiTH-R-ISY-1506, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[123] K. Forsman, Implicitization, graph ideals and control systems, Technical Report LiTH-R-ISY-1508, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[124] F. Gustafsson, Slip-based estimation of tire-road friction, Technical Report LiTH-R-ISY-1509, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[125] P. Lindskog and B. Wahlberg, Applications of Kautz models in system identification, Technical Report LiTH-R-ISY-1510, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[126] F. Gustafsson, S. Gunnarsson, and L. Ljung, On time-frequency resolution of signal properties using parametric techniques, Technical Report LiTH-R-ISY-1511, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[127] S. Andersson and A. Nehorai, Some comparisons of Cramer-Rao bounds for vector sensors and scalar sensor arrays for array processing, Technical Report LiTH-R-ISY-1512, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[128] S. Andersson and A. Nehorai, Optimal dimension reduction for array processing - generalized, Technical Report LiTH-R-ISY-1513, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

Appendix I

Master Theses (Examensarbeten)

[129] T. Sköldin, Structuring and implementation of GRAFCET in G2, Master Thesis LiTH-EX-1178, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[130] M. Eriksson, A method for work on lightning-tests on airplanes, Master Thesis LiTH-EX-1188, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[131] A. Gustavsson, Classification of objects by pole estimation of return pulse from an impulse radar, Master Thesis LiTH-EX-1191, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[132] R. Wiksten, Production of a refined washing-result signal by estimation of COD amount in the pulp, Master Thesis LiTH-EX-1192, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[133] L. Bergström, Estimation of target following filters for airplanes, Master Thesis LiTH-EX-1194, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[134] T. Finnström and P.-G. Eriksson, Exact linearization and analysis of nonlinear systems, Master Thesis LiTH-EX-1198, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[135] H. Ekström, Supervision of lung frequency through adaptive filtering, Master Thesis LiTH-EX-1205, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[136] J. Rostamy and M. af Donner, Attitude control of a mini helicopter, Master Thesis LiTH-EX-1206, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[137] C. Lindqvist, Speech recognition - speaker independent recognition of isolated words, Master Thesis LiTH-EX-1207, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[138] C. Johnson, A software controlled simulator model of the fuel system in the JAS 39 Gripen, Master Thesis LiTH-EX-1217, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[139] L. Blixt, Evaluation of the GPS-system for position calculation, Master Thesis LiTH-EX-1219, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[140] M. Samuelsson and A. Westroos, Modeling of a spray quenching system, Master Thesis LiTH-EX-1227, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[141] C. Forsander and H. Floberg, Analysis of mechanical feedback of an angle, Master Thesis LiTH-EX-1228, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[142] J. Plantin, Modelling and simulation of reticle in tracking system, Master Thesis LiTH-EX-1231, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[143] H. Olson, Aircraft maneuver detection from fluctuation radar signals, Master Thesis LiTH-EX-1233, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[144] M. Koebe, Modelling of a refining process, Master Thesis LiTH-EX-1235, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[145] A. Ericsson, Classification of simulated radar signals with neural networks, Master Thesis LiTH-EX-1236, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[146] P. Larsson, Neural nets in relay protection applications, Master Thesis LiTH-EX-1243, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[147] M. Nord, Artificial neural networks with one or more layers – a comparison, Master Thesis LiTH-EX-1250, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[148] F. Linder, Identification in the frequency plane, Master Thesis LiTH-EX-1251, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[149] C. Lagerström and A. Karlsson, Digital control strategies for voltage control in asynchronous engines, Master Thesis LiTH-EX-1252, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[150] T. Lönnqvist and P. Nilsson, Fuzzy control for rate-controlled pacemakers, Master Thesis LiTH-EX-1253, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[151] M. Torngren and G. Widlund, Reduction of nonlinear systems, Master Thesis LiTH-EX-1254, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[152] E. Andersson, Use of a microprocessor-based controller and identification using SITB, Master Thesis LiTH-EX-1257, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[153] M. Barhanko, The dynamics of a rolling mill, Master Thesis LiTH-EX-1258, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[154] M. Skoog, Tools for dimension....., Master Thesis LiTH-EX-1265, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[155] B. Kolström, Optimization of an adaptive controller for the rolling process, Master Thesis LiTH-EX-1271, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[156] M. Mentes, Identification of pilot dynamics with artificial neural networks, Master Thesis LiTH-EX-1283, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[157] M. Sjöström, Monitoring of a liquid helium supply for superconducting equipment at CERN, Master Thesis LiTH-EX-1284, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[158] J. Eriksson, Symbolic solution of the algebraic Ricatti equation, Master Thesis LiTH-EX-1285, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[159] M. Hansson, Positioning of mini helicopter, Master Thesis LiTH-EX-1286, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[160] M. Ragneberg, Automation of oretap in Svappavaara, Sweden, Master Thesis LiTH-EX-1288, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[161] Ö. Lindahl, Generation of flight patterns for control of digital aircraft model, Master Thesis LiTH-EX-1289, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[162] A. Johansson and S. Karlsson, Starting a simulation system and studying the automation of the firing of a rigidly mounted aircraft gun, Master Thesis LiTH-EX-1290, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[163] T. Andersson, A software model of the radar simulation MARS, Master Thesis LiTH-EX-1292, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[164] K. Pettersson, Identification in MATLAB with linearized airplane model, Master Thesis LiTH-EX-1294, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[165] M. Jansson, Characterization of smearing tendencies, Master Thesis LiTH-EX-1307, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[166] S. Harrysson, The structure of echo cancellation for the cancellation of nonlinearities in ISDM - interface echos, Master Thesis LiTH-EX-1310, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[167] B. Torstensson, A study of filtering and detection algorithms, Master Thesis LiTH-EX-1315, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1992.

[168] A. Stenman, Fuzzy CAT - an analysis tool for fuzzy control, Master Thesis LiTH-EX-1323, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

[169] J. Billing, Remote access to the LEP200 cryoplants, Master Thesis LiTH-EX-1361, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1993.

....AND THE WINNER IS

Professor Keith Godfrey (University of Warwick), demonstrating the solution to the estimation problem set in last year's Control Quiz.

JEOPARDY

Find the right questions to the following answers:

1. 130.236.24.1
2. $\ddot{y} + \Theta_1 u \dot{y}^3 y^2 + \Theta_2 \dot{y} y + \Theta_3 \dot{y} + \Theta_4 u y + \Theta_5 u = 0$
3. Antalya
4. January 20, 1984
5. System Identification
6. No, not if $\Theta \to \infty$
7. Modeling
8. NSHP
9. 42