LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT 1993/94

Contents

Chapter 1

Introduction

The Division of Automatic Control at Linköping University consists of some thirty 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 National Board for Industrial and Technical Development (NUTEK) and the Swedish Research Council for Engineering Sciences (TFR) for funding a major part of our research.

During the year the group has been expanding, at the same time as several of our former students have left for new challenges in industry and academia: Mats Viberg has taken up the position as Professor of Signal Processing at

Chalmers University, Gothenburg; Krister Forsman is now with the ABB Corporate Research in Lund; Sören Andersson has joined a newly formed group for adaptive arrays at Ericsson Radio Systems AB; and Torbjörn Andersson is now with SAAB Missiles AB.

The year has also been filled with various preparations for new research initiatives, relating to new funding forms in Sweden. We have been selected by NUTEK as a candidate for a "Competence Center" on Integrated Control and Information Systems (ISIS). This is a cooperation between our group, Vehicular Systems in the Department of Electrical Engineering and the Laboratories for Knowledge Representation and for Engineering Data Bases and Systems in the Computer Science Department.

Four of our graduate students have finished their Tekn.Lic. degrees during the year: Torbjörn Andersson, Håkan Fortell, Tomas McKelvey, and Predrag Pucar.

In the following pages the main research results obtained during the academic year 1993/94 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 mail-server. The procedure for this is described in the next section.

Chapter 2

Network Services

There are a number of ways you can access the work produced at this group. Most convenient is probably electronic mail to the person you wish to contact. 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 either by using our Mail Server, FTP- or World Wide Web- services. 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 that you are less sensitive to the delays on some heavily used parts of Internet.

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 the information was split into several pieces as well as decode concatenated files.

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

`ReportIndex  CompleteReportIndex`

where `ReportIndex` is a list of reports electronicly available. The file `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 `compress` which yields files with suffix `Z`. The corresponding decompression programs is called `uncompress`.

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
```

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

2.3 World Wide Web

The most powerful way to get in touch with this group is probably by using our World Wide Web service (WWW). The address to our HyperText pages is:

[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.

`http://joakim@isy.liu.se`

When you surf around in our WWW-environment you will find some general information over this group, the staff, information about undergraduate courses taught by the group and you will get the opportunity the bring home technical reports produced at this group. This is the easiest way to access the groups work, just click and collect.

Our WWW service is quite new and still under development. We look forward to your feedback regarding this service. If you have any questions or comment, please send an email to our research engineer, Magnus Sundstedt:

`masun@isy.liu.se`

Chapter 3

A Retrospective: Past Industrial Projects

Since control theory is a subject that relies heavily on abstract mathematical theories, it is important to have a clear grasp on the the connection between theory and the physical-industrial reality. The control group has therefore tried to maintain a cooperation with industry through various projects. Most of these have not been described in the annual reports. In this year's retrospective we shall review a few of the industrial projects we have been involved in over the past years.

3.1 Master Theses

The greatest contribution of industrial projects comes from the master theses made by students in the engineering programs during their last year. Some two thirds of these projects are carried out in industry with joint supervision from the company and our Division. Their character is typically to build models for simulation and control design and/or to implement a new regulator. The duration of a master thesis project is about four months. The various master theses are listed in each annual report.

3.2 Contract Research

Optimal Control of a Recovery Boiler, STFI In the mid 1980's, in a contract project from STFI (The Swedish Wood and Paper Research Institute), we studied techniques for optimal control of a recovery boiler. The basic approach was to build up a model for the boiler's performance at different operation points, by adaptive identification techniques. Data from a boiler were used for preliminary studies. The project has then been taken further by STFI, who has also tried out different modeling and control strategies. Eva Trulsson was the main person responsible for this project.

Missile Regulators, Bofors. A number of projects on control of missiles were requested by the Bofors company during the 1980's. They involved control of anti-tank and anti-aircraft missiles. An interesting feature of these systems is that they have to be treated as time variable systems due to the rapid variation of the system dynamics. The time variability can be handled by LQG theory. The project lead to the actual control laws, implemented in the missiles. Another project involved predictors for anti-aircraft guns. If high performance predictors are required, nonlinearities have to be taken into account, making extended Kalman filters interesting. Persons involved in these projects were Torkel Glad, Kjell Nordström and Svante Gunnarsson.

Protective relays, ASEA/ABB Relays In mid 1980, when digital techniques were replacing analog ones in protective relays for power transmission, we carried out several contract projects for ASEA Relays. The basic technique was to develop fail-proof algorithms for least-squares type digital processing of current and voltage signals. The aim was to detect short-circuits as well as to locate them approximately. The studies supported the digital relay products that are now sold by ABB Relays. Alf Isaksson was the principal investigator for these projects.

Stabilizing Filter for JAS 39 Gripen As part of the revision of the control system for the unstable aircraft JAS 39 Gripen, SAAB developed a non-linear filter. The objective of this filter is to better deal with the negative stability effects of the rate limiters for the control signals. During the summer of 1994, we investigated this filter from several points of view, analyzing its worst case behavior. The work was carried out by Mats Jirstrand and Krister Edström.

3.3 Current Industrial Cooperation

In addition to contract projects we are also continuously involved with industrial cooperation on several different levels. Some examples are

Tire-road friction estimation, VOLVO AB One of our biggest industrial projects has been the task to develop an estimator for the tire-road friction in automobiles. This has been done in cooperation with Volvo, and has been reported in the past annual reports. We have made a prototype, which may lead to a commercial product. See, e.g., Section 5.4 in this report. Fredrik Gustafsson is responsible for this project which is part of the Swedish RTI-program.

Radar/Laser signals for object detection, FOA In a joint project with FOA (The National Defense Research Institute) laser/radar image signals are studied. The project originated from the industrial IT4-program and is still going on. The problem is to analyze combined, reflected doppler-radar signals and laser signals to detect objects and to estimate their range. This problem involves several basic algorithmic techniques and has lead to one Tekn. Lic. Thesis, [1]. Mille Millnert and Predrag Pucar are the principal investigators for this project.

Estimation of residence time in the pulp process, Skutskär and STFI As a part of a large STFI project to build up real time data bases for the pulp factory at Skutskär, we studied data from the process to develop general techniques to estimate the residence time in buffer vessels and reactors. Off-line and on-line algorithms, involving non-linear transformations of measured data were developed. Part of a Tekn. Lic. thesis, [4], was devoted to this problem. Torbjörn Andersson and Predrag Pucar, as well as Alf Isaksson have been involved in this project.

A consortium for complex systems. We are actively involved in a industry/academia consortium on complex systems. The industrial partners are SAAB Military Aircraft, Volvo Aero Corporation, and VOAC. The objective is to understand and develop tools for the construction of complex, technical systems. Currently we investigate the landing gear controller for the JAS 39 Gripen aircraft to study design and verification issues.

Aircraft models Two recently initiated projects deal with models of aircraft/airdata properties using neural networks and with updates of Finite

Element solid mechanics models, based on flight data. Both are supported by NFFP (the National Council for Aircraft Research).

3.4 Technical Partnership

With the two companies, SAAB Military Aircraft and SAAB Missiles AB we have a formal agreement on "Technical Partnership". This is like an industrial affiliations program, aiming at a closer cooperation on several issues. Within this partnership we have, e.g., studied flight test data to model the JAS 39 Gripen Aircraft. We have also jointly developed methods for mode analysis of the vibration structure for the SAAB 2000 aircraft.

Together with SAAB Missiles, regulators taking nonlinear aerodynamics into account have been investigated. For certain simplified models an exact linearization is possible. The robustness of such a regulator can be investigated using Lyapunov techniques.

Our industrial partners also play an important role in the NUTEK project on mode-switching regulators.

3.5 Graduate Students from Industry

Recently, several initiatives have been taken in Sweden to attract people in industry to pursue doctoral studies, under joint industry-academic appointments. In our group, we currently have two such Ph.D.-students: Anders Helmersson from SAAB-Ericsson SPACE AB, and Jan Palmquist from SAAB Military Aircraft. Clearly, their presence in the group and their thesis projects form yet another bridge to industrial cooperation.

Chapter 4

System Identification

4.1 Introduction

The research in System Identification covers a rather wide spectrum, from general principles to specific algorithms and practical applications.

A book, [5] on modeling and identification has been published during the year. Two licentiate theses, dealing with identification problems have also been defended: [3] and [4]. Other general expositions include [28], [13] and [45].

Our activities in the different subareas of system identification will be surveyed in the following subsections.

4.2 Model Structure 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 [14] and [21] 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.

The bias-variance trade-off is a central topic in model validation and model selection. The traditional approach is to propose a number of candidate models and then select that one which performs best according to some criterion. In [20] another approach is presented. By introducing *regularization*, i.e., the criterion is modified by an additional penalty for large parameter values

$$W_N(\theta) = \sum \varepsilon^2 + \delta|\theta|^2 \tag{4.1}$$

then the variance-bias trade-off can be done by the choice of δ. This technique can also be utilized to avoid the problem of parameterizing multivariable systems.

The regularization can also be obtained by *premature stopping*, i.e., if a non-regularized criterion is being minimized and the numerical search for the minimum is being stopped before the minimum is reached. Then the obtained estimate will have similar properties as the minimum of 4.1. This is described in detail in [86].

Where should these premature stop be done? This is usually decided upon with help of a second data set. When the criterion computed on this second data set starts to increase then the search is terminated. This means that these data has been, partly, used in the estimation and, hence, caution has to be taken if these data are also used as validation data. [59] consider this topic and draws some conclusion about the use of validation data for model selection.

In general, model structure selection is a very difficult problem. It is crucial to choose the "right" structure in conventional identification since one postulates that the chosen structure contains the true system. However, for linear dynamical system it is the frequency function rather than the parameter estimate that is of interest. This means that a less bold alternative is to weigh together estimated frequency functions emanating from different model structures. The weights should be chosen according to how well the models fit the data. Unfortunately, no hints on how the weights quantitatively should be chosen are provided in the conventional problem formulation. However, in a Bayesian formulation this falls out automatically. An appropriate framework is developed in [15]. This scheme appears to have some attractive properties when there are several model structures that perform equally well but pick-up different parts of the dynamics. The weighted estimate then gives a more reliable accuracy estimate than if only one of these structures is chosen and from then on assumed to be correct. The scheme also allows incorporation of a priori information on the frequency function.

4.3 Neural Networks in System Identification

There has been a growing interest for artificial neural networks (NN) in various applications during the past years. Many results, well-known in statistics or other scientific fields, have been re-discovered in the NN context. NN are however just one out of many possible non-linear black-box models. What is special about them compared to more classical modeling approaches? The paper [60] sheds some light on these questions and gives an introduction to non-linear identification with NN.

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 modeling different non-linear system. This is due to regularization which can be described as

$$W_N(\theta) = V_N(\theta) + \delta \mid \theta - \theta_{\#} \mid^2 \tag{4.2}$$

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

The regularization can also be implemented by premature stopped search for the minimum of $V_N(\theta)$. This means that the iterative minimization procedure is terminated before the absolute minimum, $\hat{\theta}_N$, is reached. The model's behavior on validation data is measure of the model quality and in Figure 4.1 the root-mean-square error are depicted during the estimation for identification data and validation data respectively. The error computed on the validation data first decrease, but then, after a certain number of iterations, starts to increase again. This means that the model first becomes better and then starts to become worse again. The conclusion is that it sometimes becomes favorable to stop the iterations before the minimum of $V_N(\theta)$ is reached. The detailed explanation of this can be found in [86]. Intuitively it can be explained in the following way; The most important parameters will give the main contribution to the gradient and, hence, these parameters will converge faster than the less important parameters. If the numerical search is terminated before the less important parameters have converged then they will not contribute to the miss-fit. The efficient number of parameters will be lower than the nominal number of parameters.

4.4 Semi-Physical Modeling

The most demanding step in the identification procedure is to come up with a suitable model structure for the process and for the intended application of the model. Suggested design approaches range all from pure *black boxes*

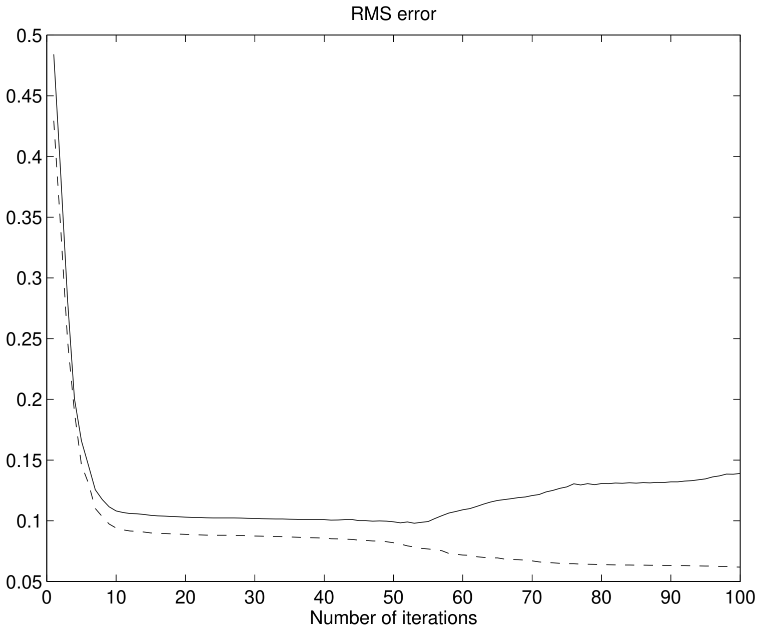

Figure 4.1: Solid line: the criterion computed on estimation data; dashed line: the criterion computed on validation data.

to fully *physically parameterized structures* (where the structure reflects all physical insight about the process and where the variables and the parameters all have direct physical interpretations). Between these two design "extremes" there is a zone where considerable and important physical insight is used in the identification procedure, but not to the extent that a formal physically parameterized model is constructed.

This is the "middle zone" considered in *semi-physical modeling*. The idea is to utilize physical insight about the underlying process in order to find adequate nonlinear transformations of the raw measurements so that the new variables – the new inputs and outputs – stand a better chance to describe the true system when they are subjected to standard model structures (typically linear in the parameters and in the new variables).

In case of an electric heater with voltage as input and temperature as output, this could simply be the matter of using the squared voltage rather than the voltage itself as input to, say, an ARX-type of model, in order to reflect the power consumption of the heater.

It could also be the matter of much more complicated transformations, that are suggested based on a *symbolic* treatment and rearrangement of basic physical laws. If the given equations are differential-algebraic there is a considerable support for such manipulations; constructive procedures from *differential algebra* (Ritt's algorithm) and *commutative algebra* (Buchberger's algorithm) are good examples of such tools. In this way, a set of physically motivated candidate regressors can be constructed. However, these are often so many that they need to be efficiently sorted and screened based on their predictive power. This typically involves a number of statistical tests, closely related to linear regression estimation and modeling. The outlined identification procedure is put forward in [55].

4.5 Identifiability

Identifiability concerns the problem to decide whether it is possible to estimate all the parameters within a given model structure from observed input output data.

A general approach to this problem has been described in earlier activity reports. It is based in *differential algebra* and uses Ritt's algorithm to transform any given parameterized model structure (linear or non-linear) to a linear regression form. If and only if this is successful, the model structure is globally identifiable. The main paper on this has now been published as [9].

A spin-off of this theory is that all identifiability questions can, from a theoretical point of view, be studied in terms of linear regression. This is used in [29] and [35] to study robust identifiability properties.

From a local, and numerical point of view, identifiability can be studied via the Information matrix (or the Hessian of the identification criterion). In [114] this is applied to an efficient algorithm for monitoring identifiability.

For model structures with discrete parameters, or cases where noise and/or input may assume only a finite number of values, the identifiability problem requires other approaches. One such approach, applied to blind equalization, is studied in [22].

4.6 State Space Methods

Models in state-space form is a model structure particularly convenient when modelling multi-input multi-output linear systems. In the prediction error framework a model is selected by minimizing a prediction error criterion by means of a parametric optimization. Traditionally much effort has been spent on the issue of minimal identifiable parameterizations of such models. This leads to a set of partially overlapping model structures. If the requirement of minimal parameterization is relaxed a full parameterization of the state-space matrices can be used which trivially leads to a model structure which covers all systems of a given order. This new approach is described in [20, 56] and [3]. The key theoretical result is that even if excessive parameters are estimated the statistical quality of the estimated predictor coincides with a standard identifiable model with a minimal parameterization. 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. This choice of realization is based on the good numerical properties of the balanced realization.

In order to successfully use the prediction error framework an initial model of high quality is required. The recent subspace based state-space identification algorithms produce state-space models of high fidelity with modest computational effort. An instrumental variable subspace approach is presented in [27] which estimates finite-dimensional models consistently for general noise covariance structures. Explicit formulas for the asymptotic pole estimation error variance is given.

4.7 Modeling Errors and Disturbances

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 modeling 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 [23] a way to estimate the random error in parametric estimates is developed. The result is a consistent estimate regardless of the bias error.

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 [6] and [24].

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 [12] and [63] 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 [42]. Furthermore, in [64] it is shown that, even if the "disturbance" is allowed to depend on the input, the worst-case cannot occur if the dynamic relation between the input and the disturbance is stable.

It is also important to take the properties of the disturbance into account when choosing the identification criterion. Since typically these properties are unknown some kind of robust criterion should be used. This problem has previously been examined from a statistical viewpoint assuming disturbances whose distributions have unbounded support. This problem is revisited in [62]. But here the distributions of the disturbances are assumed to have bounded support. It is shown that among all ℓ_p norms with $2 \leq p < \infty$, the quadratic norm ($p = 2$) is optimally robust in a minimax sense.

4.8 Model Validation

Test statistics of the type

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

where $\varepsilon(t, \hat{\theta}_N)$ is a signal that depends on a parameter estimate $\hat{\theta}_N$ are frequently used in model validation. Under the null hypothesis, the test statistic is asymptotically normal distributed. In order to determine the level of significance of the test it is necessary to estimate the asymptotic covariance of the test. However, if the parameter estimate converges, $\hat{\theta}_N \to \theta^*$, the estimated covariance matrix will be the asymptotic covariance matrix of

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

which not necessarily is the same as of the test statistic. 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 [43] where it is shown that it is possible to construct the statistics in such a way that this problem is avoided.

4.9 Frequency Domain Methods

Even though all primary measurements always are in the time domain it can sometimes be useful to consider frequency domain data as primary observations and discuss identification methods in the frequency domain. The close connection between time domain and frequency domain methods are discussed in [39, 49].

The time domain subspace identification methods can also be formulated in the frequency domain. In [94, 96, 105] a new subspace identification method using frequency domain data is introduced and analyzed. The method has successfully been applied to real data. Analysis shows that the method is consistent under weak stochastic assumptions as well as robust to norm bounded noise.

4.10 Recursive Identification

By recursive identification techniques we mean such algorithms that update the model parameter estimates on-line, at the same time as the input-output data are being measured. The archetypical algorithm for that has the form

$$\hat{\theta}(t) = \hat{\theta}(t-1) + \gamma K(t)[y(t) - \varphi^T(t)\hat{\theta}(t-1)] \tag{4.3}$$

for a linear, time-varying regression model

$$y(t) = \varphi^T(t)\theta(t) + e(t) \tag{4.4}$$

Professor Lei Guo was visiting the department during the fall of 1993, and several new results about the behavior of (4.3) were proven. A key feature in these results is that they are not, as such, asymptotic in small γ. However some of the useful, approximating expressions become more reliable as γ tends to zero. Such results are given in [10], [87] and [89].

A general study of the tracking properties of $\hat{\theta}(t)$ from (4.3) is undertaken in [7]. Aspects that relate to regularization and the choice of the matrix $K(t)$ in (4.3) are discussed in [61]. Recursive algorithms that contain the estimation of discrete parameters, like in detection and segmentation problems are dealt with in [26].

4.11 Identification and Controller Design

The activities concerning system identification and controller design can be separated into two areas. The first area is a continuation of previous work carried out together with the Department of Mechanical Engineering. The aim is to develop a control system for a large and flexible lorry crane, controlled by fluid power actuators, such that the crane can be operated in a well damped way and with good accuracy. The structure of the regulator is obtained by deriving a simplified linear model and applying linear quadratic optimization and state estimation. By evaluating the LQG regulator in the frequency domain it is found that the feedback is in fact rather simple and can be implemented using knowledge of only a moderate number of system parameters. When applying the regulator these parameters are estimated during operation of the crane. A more detailed description of the LQG regulator is given in [19] and [33]. In [34] a different but related approach is presented. Here the structure from the LQG feedback is used but the idea is to estimate the regulator parameters directly via a random search based optimization method.

The second area of research in the intersection of system identification and controller design has its origin among the schemes for iterative identification and control design that have emerged recently. A key concept in these schemes is to carry out identification using data collected in closed loop. This issue has been discussed in [40], where it is shown that, when only the bias aspect is considered, equally good results can be obtained in open loop provided that data are pre-filtered properly.

The iterative schemes have also given inspiration to more recent research. The main result from this work is a scheme where the identification step is omitted and the controller parameters ρ are updated directly. This is done by minimizing a criterion of the type

$$J(\rho) = \frac{1}{2}\mathrm{E}\left[(L_y\tilde{y}(\rho))^2\right] + \frac{\lambda}{2}\mathrm{E}\left[(L_u u(\rho))^2\right].$$

where $\tilde{y}(\rho)$ denotes the difference between the real output and the output of a reference model T_d, that means

$$\tilde{y}(\rho) = y(\rho) - T_d r$$

Furthermore L_y and L_u denote filters which can be used to give different frequency ranges of the signals different weight. Finally λ can be used to affect the magnitude of the control signal. The important idea in the proposed scheme is that the true gradient of the criterion can be obtained entirely using data from the real system operating in closed loop. A model of the real system is not needed. Under a stability condition, the scheme will converge to a stationary point of the criterion regardless of the controller structure. The scheme will be presented in a paper at CDC 1994.

4.12 Identification Tools

Identification typically requires powerful software tools of different kinds. Although the usual numerical routines will continue to form the backbone of future identification tools, such a tool must also be able to more actively aid the user throughout the modeling session.

The choice of model structure is perhaps the step in which modern computer tools are most needed. Better and more powerful modeling interfaces, especially for nonlinear systems, are means that many user's ask for. Model libraries stored in data bases and computer algebra computations also belong to the category of tools that can be of great help in this phase. Yet another interesting possibility is to employ Knowledge-Based Systems.

Another very important user aspect is "bookkeeping". The route of modeling actions leading to one specific model should, e.g., be traceable. The bookkeeping system should thus be able to keep track of what has been done in the modeling session up to now. This is a task that very well can be entrusted to an interactive graphical user interface, as is the case for the version 4 release of the System Identification Toolbox [53].

One major goal of the *semi-physical modeling* project described in Section 4.4 is to develop software tools supporting semi-physical modeling in practice. The above list of software means are currently being studied within this project [55].

4.13 Applications

During the year a number of industrial applications of different identification techniques have been reported. The applications range from vibration and flutter analysis in aerospace industry, as reported in [51], [95] and [18], via an image restoration problem presented in [52] to estimation of residence time in a paper pulp process, discussed in [58]. A comparative study of three identification methods applied to data from industrial processes are reported in [65]. In [57] it is discussed how the inter-sampling behavior of real data can be modeled and how this effects the identifications result.

Chapter 5

Signal Processing

5.1 Sensor Array Processing

During the year the research conducted in this project has been focused on two subproblems.

Polarized Seismic Wave Models

Seismological events are usually studied using records of mechanical vibrations of the earth. These vibrations may originate from natural sources such as earthquakes and volcanic eruptions or man-made sources such as explosions. To analyze the recorded data, models of waveforms are used and estimation techniques are applied to find certain parameters describing the waves. From the estimated parameters, it is possible to infer the desired information about the seismological events.

In this work ([92]), we present a model for polarized seismic waves. The physical quantity measured is the so-called *particle-displacement vector* that describes the particle motion in three dimensions at a given point in space. The parameterization of the employed model is based on two parameters describing the polarization properties of the waveforms. These are the ellipticity and the orientation angle of the polarization ellipse. We assume that the data is collected by three-component sensors (with a vertical and two orthogonal horizontal geophones, say). We state the model and compute performance bounds (Cramér-Rao and mean-square angular error) on the estimation accuracy of the parameters in the model.

Beamspace Transformation Matrix Design

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 eigen-decomposition 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. This has been demonstrated earlier in the current sensor array project. The 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.

A continuation of the above work is made in [104], where an examination is made of an approach for design of BS transformation matrices that addresses the problem of retaining as much as possible of the ultimate (ES) Cramér-Rao performance in a specified DOA-sector, while also taking into account the side lobe levels of the BS beam pattern outside this sector.

5.2 Using Power Control to Fight Rayleigh Fading in a Cellular Phone System

In an urban area, the channels used for mobile telephony are subject to Rayleigh fading due to multi path wave spreading. This will result in variations of the quality of the signal (usually measured in C/I - Carrier signal power/Interference signal power) when the mobile moves. The value of the gain can be approximated with a signal with Rayleigh distribution. When the speed of the mobile is large enough, the time periods when the quality of the signal is too low will be so short that the problem can be neglected. However, when the mobile is moving with low speed, for instance walking speed, this will cause a loss of contact for short periods of time for the user. If the dips of the channel quality can be predicted, one way of fighting this problem is to increase the power when needed. Similarly, the power can be reduced when C/I is high, which will result in lower total energy consumption plus less interference with other mobiles using the same frequency. Since the request of higher/lower power has to be coded with a very limited number of data bits (one or maybe two), delta modulation has been used in simulations showing positive results. However, other types of coding combined with adaptation in the transmitter could further improve these results.This project is a collaboration with Ericsson Radio Systems.

5.3 State Order Estimation for Hidden Markov Models

In our work in the area of segmentation of 2D structures, and as a test case the segmentation of laser range radar images, the problem of deciding which state order of the hidden Markov model (HMM) should be used is a frequently occurring one. Let us first state the definition of a hidden Markov chain

Definition: *A HMM is a doubly stochastic process with one underlying process that is not observable, but can only be observed through another set of output processes that produce the observed data. The underlying hidden process is a Markov chain.*

The HMMs are being used extensively in a variety of areas. The standard issue is how to estimate the parameters in the model producing the output and how to estimate the not observed Markov chain sequence. An often circumvented problem is how to decide on how many states to use in the assumed hidden Markov chain. In practice, when one is confronted with a, *e.g.*, segmentation problem, that kind of information is seldom known. It is, however, crucial for the result of the applied algorithm.

In [1] we give three examples of techniques that can be used for state order estimation of hidden Markov models. The methods are also verified against real laser range data, and the computational burden of the three methods is compared. Two techniques, Maximum Description Length and Maximum *a Posteriori* Estimate, are shown to coincide under certain circumstances. The third technique is novel in this context.

The following subsections contain a short presentation of the three investigated techniques.

Three Algorithms

In this subsection the three proposed algorithms are presented. The complete derivation of the expressions will be left out. The hidden Markov sequence will be denoted by $z_{t_1}^{t_2}$, meaning the sequence from time instant t_1 to t_2. The subscript is suppressed when $t_1 = 1$, and the superscript is suppressed when $t_2 = t_1$. The observed process is denoted by $y_{t_1}^{t_2}$.

Information Theoretic Techniques

Assume a sequence y^N is given and we know it has been generated by a finite state source, but we do not know the number of states M. In the sequel M will denote the "true" value of the model state order, m is the auxiliary variable denoting the model state order which is tested by the algorithm and $\hat{m}$ the estimate of the model state order. Usually a criterion is calculated for different values of m and then an $\hat{m}$ is chosen as an estimate. The desired result is, of course, that $\hat{m} = M$.

Assume that for every m we have a code Φ_m. A code can be described as a mapping from the source symbols to a series of bits. The mapping takes into account the distribution of the symbols. All the information theoretic techniques boil down to finding an appropriate code Φ_m for coding the sequence y^N, calculating the code length for different codes and then picking the m for which the code Φ_m gives the shortest code length when coding y^N. We have chosen the minimum description length (MDL) as coding principle. Shortly, the MDL principle can be summarized as choosing the model that minimizes the number of bits it takes to describe the given sequence. Note that not only the data are encoded, using the model, but also the model itself, *i.e.*, the real-valued parameters in the model.

The final, approximate, expression to minimize is

$$V = \log_2 \left(\frac{1}{N} \sum_{i=1}^{N} e_i^2 \right) + (d + M(M-1) + 1) \frac{\log_2 N}{N}.$$

Predictive Least Squares

In this brief overview we will only describe the predictive least squares (PLS) idea, and indicate its application on state order estimation of HMMs. Again, a full description of the derivations is given in [1]. We start with a basic regression problem. Assume two sets of observations y^N and $x^N(i)$, where $i = 1, \ldots, M$, are given. The usual procedure when applying least squares is to introduce a model class and to pick a predictor for y_t. The predictor is denoted by $\hat{y}_t(\theta; y^{t-1})$. The ideal predictor should then minimize

$$E_\theta (y_t - \hat{y}_t(\theta; y^{t-1}))^2. \tag{5.1}$$

If the expectation in (5.1) is replaced with a sample mean the following estimate is obtained

$$\hat{\theta} = \arg\min_\theta \frac{1}{N} \sum_{t=1}^{N} (y_t - \hat{y}_t(\theta))^2. \tag{5.2}$$

The PLS approach is to change the predictor to $\hat{y}_t(\theta_{t-1}; y^{t-1})$, *i.e.*, at every time instant the parameter vector θ minimizing the criterion (5.2) is calculated using past data only. The parameter vector estimate will vary in time, since the number of data on which it is based, grows. If then all the prediction errors are accumulated we the following criterion is obtained

$$V_{PLS}(m) = \sum_{t=1}^{N} (y_t - \hat{y}_t(\theta_{t-1}; y^{t-1}))^2,$$

where m is the number of regressors x included. In our work we show how the PLS idea can be applied in the HMM state order estimation problem, and compare it by simulations with the other two suggested criteria.

Maximum a Posteriori Estimate

The last approach is based on using a bank of Kalman filters when estimating the model parameters of the model behind the observed data, and the state sequence. The Kalman filters also give the distribution of the estimates, so for example the distribution of the data assuming no underlying Markov chain is given by the following expression

$$P(y^N) = (2\pi)^{N/2} \left(\prod_{i=1}^{N} \det S_t \right)^{-1/2} e^{-\frac{1}{2}V_N},$$

where S_t is given by the following equations

$$\begin{aligned} S_t &= \varphi^T P_{t-1} \varphi_t + \Lambda_t \\ P_t &= P_{t-1} - P_{t-1} \varphi_t S_t^{-1} \varphi_t^T P_{t-1}, \end{aligned}$$

V_N is the normalized sum of prediction errors and φ is a known vector.

When a Markov chain with M states is introduced, and after some calculations, the following expression for the likelihood of the data is obtained

$$-\frac{2}{N} \log P(y^N | z^N, M) \approx \frac{1}{N} \sum_{i=T_1}^{T_M} V_{N(i)} + \frac{1}{N} \sum_{i=T_1}^{T_M} d(i) \log N(i).$$

In the expression above $d(i)$ denotes the number of parameters of the output process model corresponding to different Markov chain states, T_i denotes the set of time instants where the Markov chain is in state i and $N(i)$ denotes the number of elements in T_i. Knowledge about the transition matrix can readily be included in the loss function above, in the sense that very unlike state sequences is penalized more than an *a priori* likely one.

Example

Here the MDL approach is tested using an image obtained by a laser range radar. The pixel values are the distance to the terrain measured by a laser. The objective with the segmentation algorithm, in this case the EM algorithm, is to find objects in the image that differ from the background, in other words a first step towards object recognition. The test image that is used here shows a shield in the middle of the image, and in the upper right corner there are some bushes. The way to interpret the segmented image is to look at connected areas with the same segment label, and then do further investigation by taking the estimated parameters of the observed model, variance of the residuals, *etc*, into account. The problem we are stressing here is that usually the user has to pick the number of hidden states of the Markov chain for each row (or fix one for all rows) since the image is segmented

Figure 5.1: Left: The raw data obtained from the laser system. The z-axis is the distance to the terrain. Right: Resulting segmentation of the laser range radar image using the EM algorithm and the MDL strategy.

row by row. Here we used the above proposed MDL loss function. Similar results are obtained by using the MAP loss function. The estimation routine, however, is different in that case. In Fig. 5.1 the original laser image and the resulting segmentation is shown. Note that in the area "in front" of the shield only one hidden state is used, and that way spurious jumping is avoided.

5.4 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 per mille), 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.

The prototype has been demonstrated in various places in connection with the European RTI program. See Volvo's information sheet on the next page.

Chapter 6

Nonlinear Systems

6.1 Algebraic Approaches in control

Classically nonlinear systems have been described by nonlinear differential equations like

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

The analysis is greatly simplified by the fact that the derivative $\dot{x}$ appears explicitly in the left hand side. However it is not at all certain that one arrives at a description like this one when modeling a physical system. An example which is described in [16] is shown in Figure 6.1. The resistors are nonlinear elements described by

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

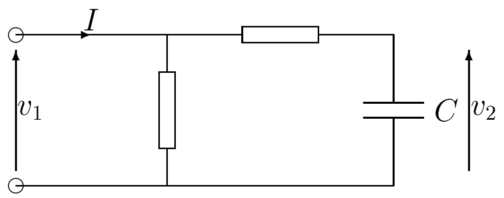

Figure 6.1: Electric circuit with nonlinear resistors

where v is the voltage over the resistor and i is the current. Suppose for simplicity that $C = 1$. Then the circuit is described by

$$\begin{aligned} I &= g(v_1) + g(v_1 - v_2) \\ \dot{v}_2 &= g(v_1 - v_2) \end{aligned} \tag{6.1}$$

This is not a standard state space description because it contains one static and one differential equation.

The mathematical theory of differential algebra gives an algorithmic approach to the handling of such systems for the case of polynomial differential equations. An overview is given in [16]. The standard description is not the state space one but something called a characteristic set. For the example of Figure 6.1 there are several possible choices of characteristic sets, for instance

$$g(v_1) + g(v_1 - v_2) - I = 0$$

$$\dot{v}_2 - \left(-v_2^3 + 3v_1v_2^2 - 3v_1^2v_2 + 3v_2 + 3I\right)/6 = 0$$

Another possibility is

$$1728\dot{v}_2^3 - 1080v_2^3\dot{v}_2^2 + 2592v_2\dot{v}_2^2 - 1296\dot{v}_2^2 +$$

$$+144v_2^6\dot{v}_2 - 432v_2^4\dot{v}_2 + 540v_2^3\dot{v}_2 - 1296v_2\dot{v}_2 + 324\dot{v}_2 +$$

$$+8v_2^9 - 144v_2^7 - 36v_2^6 + 648v_2^5 + 108v_2^4 - 810v_2^3 + 162v_2 - 27 = 0$$

together with

$$-12v_1v_2 - 12v_1\dot{v}_2 + 3v_1 + 4v_1v_2^3 - 2v_2^4 + 6v_2^2 - 6v_2 + 6v_2\dot{v}_2 = 0$$

Note that in this second case the first equation contains v_2 only. It is thus possible to eliminate variables and get explicit expressions using differential algebra. Some related questions are treated in [98].

The elimination procedure indicated above can also be used to investigate identifiability of dynamical systems. By eliminating all variables except inputs, outputs and one parameter, one can see explicitly how that parameter depends on the known quantities. This procedure is described in [9], see also section 4. The identifiability theory can also be developed into an algorithm for robust identification, see [29], [35].

For systems that are on the standard state space form

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

with f and h polynomial or rational functions, it is usually not necessary to use the complete differential algebraic machinery. Instead one can use the state equations to eliminate derivatives successively, to get problems of ordinary algebra or algebraic geometry. Algorithmically they typically lead to Gröbner base calculations. A general overview of this type of calculation is given in [31]. The question of algebraic observability, algebraic relations between lower order derivatives and different state space realizations, is treated in [17]. It has consequences for the actual algebraic calculations in the Maple routine package Polycon, [36]. The algebraic approach can also be used to calculate solutions of the algebraic Riccati equation, [37].

6.2 Zero Dynamics

The zero dynamics is a property of affine nonlinear systems, i.e., systems of the form

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \tag{6.2}$$

which have been extensively studied during the last decade. The zero dynamics can be defined as the simplest description of the dynamics that remains when we want to keep the output to zero. The name zero dynamics comes from the fact that the zero dynamics for a linear system is another linear system whose eigenvalues exactly correspond to the zeros of the original system.

The properties of the zero dynamics are important in several control related contexts. For instance when performing exact linearization we get the input-output behavior

$$\begin{aligned} \dot{\xi} &= A\xi + Bv \\ y &= C\xi \end{aligned} \tag{6.3}$$

However, we also get an unobservable part described by

$$\dot{\eta} = q(\eta, \xi, v) \tag{6.4}$$

The zero dynamics is then given by

$$\dot{\eta} = q(\eta, 0, 0) \tag{6.5}$$

which means that the stability of the zero dynamics is crucial. The stability of the zero dynamics is also a necessary condition for the existence of various stabilizing controllers for the system (6.2).

So far the zero dynamics has mostly been studied from a differential geometric point of view. What is studied here are other aspects of the zero dynamics. First one can consider how zeros of the sequence of transfer functions

$$(H_1(s_1),\ H_2(s_1,s_2),\ldots,H_n(s_1,\ldots,s_n),\ldots) \tag{6.6}$$

that emerge from the Laplace transform of the regular kernels in a Volterra series are connected to the zero dynamics. We show in [80, 2] that if certain factorizations of the numerators can be performed, then zeros in the right half plane give an unstable zero dynamics. This can evidently be viewed as a generalization of the linear case.

Another thing which we investigate is what implications the framework of differential algebra has on the zero dynamics. In particular we study one of the most important tools of differential algebra, namely the Ritt algorithm. This algorithm calculates a simplest set of polynomial differential equations, given some ranking of the variables. In [2] we show how the Ritt algorithm can be used to calculate the zero dynamics. One problem here is that the tools from differential algebra can only be used for polynomial differential equations. To be able to use the Ritt algorithm for more general systems we study systems (6.2) where $f(x)$, $g(x)$ and $h(x)$ can be described by polynomial differential equations. We replace the non-polynomial functions with a new variable and add their polynomial differential equation to the system description. It is shown that if the Ritt algorithm is applied to this new system and we afterwards replace the new variable with its non-polynomial origin, we get exactly the same zero dynamics as we would have if we had used differential geometry.

6.3 Robust Analysis and Design using μ-Methods

One general method for stability analysis and design of nonlinear systems is the Lyapunov technique. This approach can also be applied to problems where performance bounds are to be assured [50, 101].

Linear problems are often handled using quadratic Lyapunov functions (LQG and H_∞). Related to this is the concept of structured singular values, or μ, which can be seen as an extension to H_∞ methods. These new methods have attracted considerable interest since their introduction in 1982. The μ analysis can be seen as a refinement of the small gain theorem. We can include knowledge about the structure of the uncertainty by treating the uncertainties as separate elements with different characteristics.

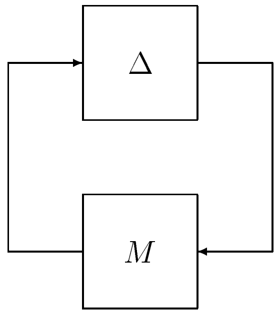

Figure 6.2: System with uncertainties. The Δ block has a diagonal block structure, where each block may have different characteristics.

The system is modeled as an augmented system with feedback loops containing the parameter variations, uncertainties and perturbations, see Figure 6.2. Using this formalism with are able to capture a quite general class of models. For instance nonlinear systems can in some cases be modeled as a linear system with nonlinear "uncertainty" elements in the feedback path. Also, performance bounds can be included similarly.

Recently linear matrix inequalities (LMI) have emerged as an important tool for μ analysis. The LMI formulation has a number of nice features making it attractive for control problems. Its solution set is convex, which implies that we always can find the global solution. Also, efficient methods for solving this type of problem have become available recently.

Both when computing the robustness bounds and in the synthesis task, scaling matrices play an important role. The scaling matrices have a structure corresponding to the uncertainties. For constant uncertainties the scaling matrices may be frequency dependent. One way of describing this is to let the scalings be parameterized by a state-space model [97].

LMIs can also be used for solving the H_∞ synthesis problem. The model reduction problem can be seen as a special kind of H_∞ synthesis in which the order of the controller is constrained. This can be formulated as a matrix inequality problem, unfortunately not linear in its unknown parameters. However, an iterative method has been proposed [93] that improves the approximation error compared to Hankel norm model reduction in some cases.

6.4 Fuzzy Control

Recently controllers based on fuzzy logic have become popular. Nonlinear relations are described using a number of statements of the form "when the error is small, and the derivative of the error is large, then the control signal is rather small and negative". These statements are then converted into a mathematical description using so called membership functions. The Maple package FuzzyCAT, [38], [48], [110], makes it possible to compute this relationship explicitly and then use classical control theory tools to analyze the control system. It thus acts as a bridge between the fuzzy logic description and more classical ways of looking at control systems.

Chapter 7

Physical Modelling of Hybrid Systems

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.

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 *et cetera.* 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 *composition* in which phase the above relations are composed to form 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.

7.3 Hybrid Systems

Abrupt changes in the dynamic behavior of physical systems are ubiquitous in engineering applications. In fact, many engineering devices are designed intentionally to obtain near ideal switching behavior *e.g.* electrical relays, diodes, mechanical clutches, free wheeling devices, solenoid valves, check valves *et cetera*; 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.

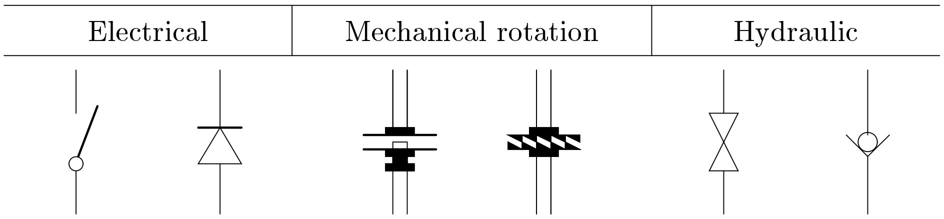

Figure 7.1: Some explicit discrete devices.

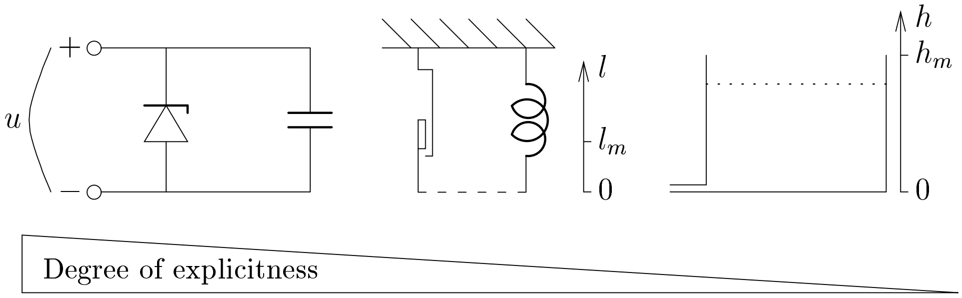

Figure 7.2: A spectrum of mode switching phenomena.

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 behavior (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 behavior 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* [30, 46, 111].

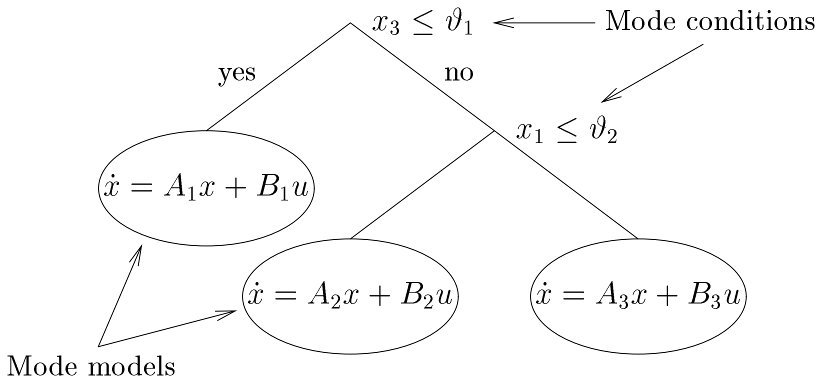

Figure 7.3: A model tree as a mode invariant representation.

7.4 Reticulating Hybrid Systems

We have noticed that discrete phenomena typically affect the 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 behavior. 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 is possible, and if so, how to extend the set of physical concepts to sanction this distinction in mode switching systems as well.

In *e.g.* [32, 70] 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.

The **Sw**-element has two distinct *states*, namely the *effort* ($\mathcal{E}$) and the *flow* ($\mathcal{F}$) state. In state $\mathcal{E}$ it acts as an ideal effort source with zero output (**Se** : 0) and in state $\mathcal{F}$ it acts as a flow source, also with zero output (**Sf** : 0). 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 denote 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). Here the damper r_1 and the spring k_1 represents the wheel itself

Applying the systematic method of mapping ideal mechanical models 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 classical bond graphs are carried over to 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 [44, 69, 81, 47, 112]. We now have a complete computational model of the touch-down-process.

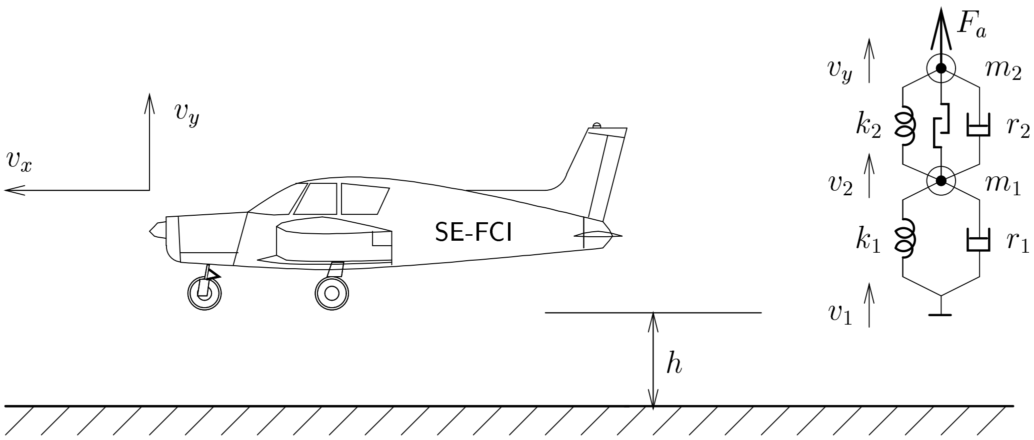

Figure 7.4: A hybrid system (left) and a reticulation of the same (right). m_1 is the mass of the wheel and damper sub-system and m_2 is the mass of the mainframe. F_a is the aerodynamic force acting on the mainframe.

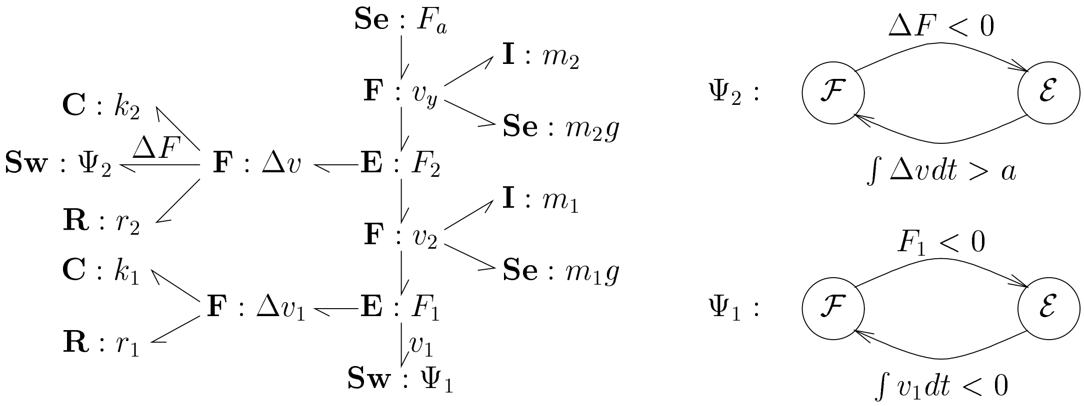

Figure 7.5: The acausal switched bond graph (left) and the control structures (right) of the landing aircraft system.

Chapter 8

Symbolic Control

8.1 A Polynomial Approach

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 flavor from 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

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

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 analyze 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.

8.2 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.

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 we focus on basically excludes such processes as described above. The exact class studied is defined through explicit conditions on the actions and a description can be found in [41, 71]. The paper presents a planning tool that generates minimal plans (in terms of length). The generated plan show maximal parallelism and is generated as a Grafcet chart. The complexity of the algorithm increase polynomially with the number of state variables.

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`

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`

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. His research interests include algebraic and algebro-geometric aspects of nonlinear systems theory, especially in connection with computer algebra. Since September 1994 he is with ABB Corporate Research in Lund, Sweden.
email: `krister@crclund.abb.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. He is currently employed by Ericsson Radio Systems, Stockholm, Sweden.
email:
`Soren.andersson@era-t.ericsson.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 and his Ph.D. in 1994.
email: `janerik@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 symbolical and numerical calculations in the optimal filtering and the linear optimal control problems.
email: `ke@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 his 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 and his Licentiate's degree in 1994. He is currently employed by Saab in Linköping.
`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 in 1991 and his Licentiate degree in 1994, both from Linköping University. His current research interest is the field of 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 and his Licentiate degree in 1994 at Linköping University. His current research interests are in System Identification focusing on state-space models and subspace based methods both in the time and frequency domain.
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`

Anders Helmersson was born in 1957. He received his M. Sc. in 1981 Applied Physics at Lund Institute of Technology. He has been with Saab Ericsson Space since 1984. Since 1993 his also joined the Control Group as part time Ph.D./ student. His research interest is mainly in robust control and gain scheduling.
email: `andersh@isy.liu.se`

Krister Edström was born in 1969. He received his M.Sc. in Applied Physics and Electrical Engineering in 1993 from Linköping University. His current research interest is in the field of modelling.
email: `edstrom@isy.liu.se`

Mats Jirstrand was born in 1968. He received his M.Sc. in Applied Physics and Electrical Engineering in 1994 from Linköping University. His current research interest is nonlinear systems.
email: `matsj@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.

Steve Niu was born in 1964. He received his BSc in engineering from the Department of Automation at Tsinghua University of China in 1985, and PhD degree in process control from the Department of Chemical Engineering at the University of Alberta of Canada in 1994. He is currently a guest researcher in the department. His research interests include control-oriented system identification, adaptive/predictive control, and signal processing.

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. Since January 1994 he is employed by Domstolsverket in Jönköping, Sweden.
`email: patrik@isy.liu.se`

Magus Sundstedt was born in 1970. He received his M.Sc. in Applied Physics and Electrical Engineering 1993 at Linköping University, Department of Electrical Engineering. As a research engineer he is responsible for the computer network and the laboratory equipment.
email: `masun@isy.liu.se`

Ingegerd Stenlund and Ulla Salaneck are secretaries for the control group.
email: `ingegerd@isy.liu.se` and `ulla@isy.liu.se`

Appendix B

Courses

B.1 Undergraduate Courses

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

Automatic Control. The basic control course given for all engineering programs. *Contents*: The feedback concept. PID-controllers. Frequency domain design techniques. Sensitivity and robustness. State space models and state feedback controllers. Observers.

M Mechanical Engineering Program. 140 participants. Lecturer: Inger Klein.

Y Applied Physics and Electrical Engineering. 180 participants. Lecturer: Mille Millnert.

D Computer Engineering Program. 120 participants. Lecturer: Håkan Hjalmarsson.

Im Industrial Engineering and Management, Mechanical variant. 80 participants. Lecturer: Krister Forsman.

Ie Industrial Engineering and Management, Electrical variant. 60 participants. Lecturer: Roger Germundsson.

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.

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: Jan-Erik Strömberg.

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.

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

The Engineering program

A 2-year program leading to a University Diploma in Engineering. (Electrical Engineering, EI, Mechanical Engineering, MI)

Automatic control, EI 5 units, 70 participants. Contents: Dynamical systems, the feedback principle, frequency domain analysis and design of control systems, robustness and sensitivity of control systems, sampling, implementation, some examples of nonlinearities in control systems. Simulation of dynamic systems. Lecturer: Kent Hartman.

Automtic control, advanced course, EI 2 units, 70 participants. Contents: Sequential control and logic controllers. A typical industrial control system. Lecturer: Kent Hartman.

Automatic control, MI 4 units, 50 participants. Contents: Sequential control and logic controllers. Fundamentals of automatic control, dynamical systems, feedback, differential equations, frequency analysis, Bode plots, stability, simple controllers, sampling, implementation, simulation of dynamic systems. Lecturer: Kent Hartman.

B.2 Graduate Courses

Algebraic Methods in Control. Lecturer: Torkel Glad. Literature: Lecture notes

Linear Systems, Prentice Hall, Inc. Englewood Cliffs, N.J. 1980.

System Identification. Lecturer: Lennart Ljung. Literature: L. Ljung, System Identification – Theory for the User, Prentice hall, 1987.

Linear Estimation and Recursive Identification. Lecturer: Lennart Ljung. Literature: B. D. O. Anderson, J. B. Moore, Optimal Filtering, Prentice Hall 1979.

Nonlinear Systems Lecturer: Torkel Glad. Literature: Lecture Notes on Nonlinear Systems.

Appendix C

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 5 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. The students also got 24-hours access to some 60 SPARC-stations 10 computers in an Ethernet based computer network.

Comments and questions on the equipment can be directed to Magnus Sundstedt.

The computer network at the Division of Automatic Control consists of the following components.

- An Ethernet based 10baseT TCP/IP network
- 1 Sun SPARCsystem 300 server
- 1 SPARCstation 10
- 16 SPARCstation 5
- 5 SPARCstation LX
- 5 SPARCstation 2
- 5 SPARCstation ELC
- 4 SPARCstation SLC

- 1 SPARCstation 1+
- 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 ArborText, Inc. and FrameMaker from Frame Corporation are other document handling packages that the network offers. The public services available (e.g. anonymous ftp areas, mail server and WWW) are described in Section 2 of this report.

The laptop computers are:

- 1 Texas TravelMate 3000 WinSX
- 2 Texas TravelMate 4000 WinSLC
- 2 Texas TravelMate 4000 WinDX2

In the laboratory the following processes and computers are used:

- 16 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
- 2 inverted pendulum processes

- 1 bandmachine process
- 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
- 3 AST Bravo 486 computers with Allan Bradley SLC500 PLC system
- 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

Research in Automatic Sensor Interpretation at the George Mason University C3I Center **Professor Clay Stewart**, Dept of Electrical & Computer Engineering, George Mason University, Fairfax, Virginia. August 23, 1993.

The Russian Silicon Valley **Professor Alexander Piskunov**, Moscow Institute of Electronics Technology, Moscow, Russia, August 30, 1993.

Errors in Variable Models **Wolfgang Scherrer**, Institute of Econometrics, University of Vienna, Vienna, Austria. August 26, 1993.

On Finite Memory Estimation **Dr Alexander Medvedev**, Division of Automatic Control, Luleå Institute of Technology, Luleå, Sweden, August 27, 1993.

Mini course in Optimal and Suboptimal Techniques for Sensor Array Signal Processing **Professor Mats Viberg**, Chalmers Institute of Technology, Göteborg, Sweden, August 31 - September 1, 1993.

Signal Treatment in ESM/SECM Receivers **Lennart Nyström**, FOA, Linköping, Sweden. September 16, 1993.

Simultaneous Stabilization: An Unsolvable Question in Linear Systems Theory **Vincent Blondel**, CESAME, Louvain la Neuve, Belgium, October 28, 1993.

Stability of Random Linear Equations with Applications to Adaptive Estimation. **Professor Lei Guo**, Chinese Academy of Science, Beijing, P.R.

China. November 5, 1993.

Convergence of Least Squares and Related Problems. **Professor Lei Guo**, Chinese Academy of Sciences, Beijing, China, November 18, 1993.

Identification and Control of GaSa Crystal Growth. **Professor Doug Looze**, University of Massachusetts, Amherst, Ma. November 30, 1993.

Adaptive Radio Network Control. **Tony Larsson**, Ericsson, Linköping. December 9, 1993.

On Recent Trends in Dynamic Feedback Control. **Joachim Rudolph**, Stuttgart, Germany, December 2, 1993.

Information Technology in Cars **Ulf Palmqvist**, Volvo AB, Göteborg, Sweden.

Structured Total Least Squares Problems in System Theory and Control. **Dr Bart de Moor**, ESAT-SISTA, Katholike Universiteit, Leuven, Belgium, January 20, 1994.

Interplay Between Identification and Control Design. **Professor Michel Gevers**, CESAME, Louvain la Neuve, Belgium, January 25, 1994.

Presentation of an Iterative Identification and Control Design Scheme. **Professor Michel Gevers**, CESAME, Louvain la Neuve, Belgium, January 25, 1994.

On the Role of Parameterization in Reducing Finite Word Length Effects. **Professor Michel Gevers**, CESAME, Louvain la Neuve, Belgium, January 26, 1994.

Is Automatic Control Useful in the Power Transmission Area? **Rina Navarro-Adelmo**, Department of Automatic Control, Chalmers Institute of Technology, Göteborg, Sweden, March 3, 1994.

L-Infinity Optimal Contraction Control. **Anders Malmgren**, Automatic Control, Uppsala University, March 10, 1994.

Ill-Conditioned Plants - Challenge problem for Identification. **Elling W. Jacobsen**, Department of Automatic Control, Royal Institute of Technology, Stockholm, Sweden. March 30, 1994.

Chaos and Tangles in Dynamic Systems. **Erik Skarman**, Saab Missiles, Linköping, April 14, 1994.

A Neural Network Approximation of a Chaotic Time Series. **Henrik Saxen**, Turku Academy, Turku, Finland. April 7, 1994.

Analysis of Pressure Fluctuations to Characterize the Flow Pattern in a Fluidized Bed Combustor. **Filip Johnsson**, Department of Energy Conservation, Chalmers Institute of Technology, Göteborg, Sweden, May 5, 1994.

Topics in Digital and Robust Control of Linear Systems **Dr Bo Berhardsson**, Lund Institute of Technology, Lund, Sweden, June 8, 1994.

A Formula for Computation of the Real Stability Radius. **Dr Bo Berhardsson**, Lund Institute of Technology, Lund, Sweden, June 8, 1994.

On a Relationship Between the Inverse of A Stationary Covariance Matrix and the Linear Interpolator. **Professor Raj Bhansali**, Department of Statistics and Computation Mathematics, The University of Liverpool, Liverpool, UK. June 10, 1994

Convergent Approximation of the Optimal Recursive Parameter Estimator. **Professor Donald M Wiberg**, Department of Electrical Engineering, UCLA, Los Angeles, Ca. June 13, 1994.

Appendix E

Travel and Conferences

Lennart Ljung participated in the IFAC Congress in Sydney, Australia, July 19-23. He took part in the European Research Network on System Identification, ERNSI (meeting) in Louvain-la-Neuve, September 29 to October 1. He then participated in the MatLab Conference in Cambridge, Massachusetts, October 18-20, and in the IEEE Conference on Decision and Control in San Antonio, Texas, USA, December 15-17. March 21-24 he took part in the IEE Control'94 Meeting in Warwick, United Kingdom and April 15-16 he participated in the conference in the Honor of Harold Kushner's 60th birthday, held in Newport, Rhode Island, USA

Torkel Glad participated in the European Control Conference in Groningen, The Netherlands, June 28–July 2, 1993 and in the MTNS'93 conference in Regensburg, Germany, August 2–6. He also took part in an Italian-Swedish workshop on identification, September 2–3.

Svante Gunnarsson visited Universite Catholique de Louvain, Louvain-la-Neuve, Belgium, during September and October and took part in the European Research Network on System Identification, ERNSI (meeting) in Louvain-la-Neuve, September 29 to October 1. He visited Satt Control, Malmö, January 14 and Scanraff Refinery, Lysekil, May 16.

Fredrik Gustafsson visited Hannover University and Wolkswagen, July 5-6, 1993. He attended the IFAC World Congress in Sydney in July 1993. He visited Volvo September 16, October 8, November 10, 23 and 24 1993. He also visited Newcastle University as a guest researcher January 24 to August 17, 1994.

Håkan Hjalmarsson participated in the IFAC Congress in Sydney, Australia, July 19-23. September 6 he visited Stuttgart University. He took part in the PAI/IUAP-17 Network on Systems and Control study day September 24 and in the European Research Network on System Identification, ERNSI (meeting), September 29 to October 1, both at Louvain-la-Neuve, Belgium. He then participated in the IEEE Conference on Decision and Control in San Antonio, Texas, USA, December 15-17. March 2-4 he took part in the 13th Benelux meeting on Systems and Control and March 29 he visited the Mechanical Engineering Systems and Control Group at Delft University of Technology. During the period September 1 - March 31 he visited the Centre for Systems Engineering and Applied Mechanics, Louvain University, Louvain-la-Neuve under a grant from the Belgian Programme on Interuniversity Poles of Attraction (PAI).

Kent Hartman attended the Ingenjörsforum i samarbete med Högskolan i Växjö "Nya ingenjörer för framtidens industri", October 25-26, 1993 and the Ingenjörsforum i samarbete med Högskolan i Halmstad "Projektorienterad utbildning", June 6-7, 1994.

Krister Forsman attended the symposium MTNS in Regensburg, Germany, in August 1993. In December 1993 he participated in the 32nd IEEE Conference on Decision and Control in San Antonio, Texas. He visited the Department of Mathematics at the University of Groningen and the Technical University of Eindhoven, both in the Netherlands, during May 1994.

Inger Klein participated in the IEEE Conference on Decision and Control in San Antonio, Texas, USA, December 15-17.

Sören Anderson returned in February from his year as a post-doctoral associate at Yale University, USA.

Anders Helmersson participated in the 1995 ACC Conference in Baltimore, Maryland, June 29-July 1, 1994. He also visited Lund Institute of Technology, October 22, 1993.

Jan-Erik Strömberg attended the IEEE International Conference on Systems, Man and Cybernetics, Le Touquet, France, October 17, 1993, Reglerteknik, Chalmers Tekniska Högskola, Göteborg, Sweden, January 21, 1994, Volvo Aero Corporation and Voac Hydraulics AB, Trollhättan, Sweden, February 3, 1994 and the European Simulation Multiconference, Barcelona, Spain, June 1, 1994.

Predrag Pucar participated in the European Research Network on System

Identification, ERNSI (meeting) in Louvain-la-Neuve, September 29 to October 1. He visited the research team of the Istituto per Ricerche di Dinamica dei Sistemi e di Bioingegneria, of the Consiglio Nazionale delle Ricerche in Padova, Italy, April 11-15. May 9-10 he took part in the Workshop for the NUTEK "Telekommunikation" frame program in Lund, Sweden.

Jonas Sjöberg took part in the European Research Network on System Identification, ERNSI (meeting) in Louvain-la-Neuve, Belgium, September 29 to October 1. He participated in the International Symposium on Forcasting, June 12-15, Stockholm, Sweden.

Tomas McKelvey Participated in the Second workshop of the European Research Network on System Identification (ERNSI), in Louvain-la-Neuve, Belgium, September 29 to October 1.

Anders Ericsson participated in the European Research Network on System Identification, ERNSI (meeting) in Louvain-la-Neuve, Belgium, September 29 to October 1. He also took part in the Workshop for the NUTEK "Telekommunikation" frame program in Lund, Sweden, May 9-10. Finally he attended IEEE 44th Vehicular Technology Conference VTC'94, in Stockholm, Sweden, June 8-10.

Johan Gunnarsson and *Jonas Plantin* participated in the 11th International Conference on Analysis and Optimization of Systems, Discrete Event Systems in Sophia-Antipolis, June 15-17, 1993.

Ingegerd Stenlund and Ulla Salaneck participated in the"Sekreterarträffen" in London in September, 1993.

Appendix F

Lectures by the Staff

Torkel Glad: *Identifiability implies robust identifiability*, ECC'93, Groningen, the Netherlands, July 1, 1993.

Lennart Ljung: *The Process of Identification*, Plenary Address, The IFAC Congress, Sydney, Australia, July 21, 1993.

Lennart Ljung: *On the Use of Regularization in System Identification*, 12th IFAC World Congress, July 22, 1993, Sydney, Australia.

Fredrik Gustafsson: *21 ML Estimators for Model Structure Selection*, 12th IFAC World Congress, July 1993, Sydney, Australia.

Fredrik Gustafsson: *Identifiability in Blind Equalization*, 12th IFAC World Congress, July 1993, Sydney, Australia.

Fredrik Gustafsson: *On the Estimation of Discrete Parameters in Linear Systems*, 12th IFAC World Congress, July 1993, Sydney, Australia.

Torkel Glad: *Constructive Algebra and Control Theory*, MTNS'93, Regensburg, Germany, August 4, 1993.

Krister Forsman: *Constructive Algebra and Control Theory*, MTNS'93, Regensburg, Germany, August 1993. (Together with T. Glad).

Lennart Ljung:*Identifiability of Systems, using Differential Algebra*, The Swedish Italian Control Meeting, Stockholm, Sweden, September 3, 1993.

Torkel Glad: *Identifiability and Differential Algebra*, Italian-Swedish Workshop on Identification, September 3, 1993.

Håkan Hjalmarsson: *Model Quality Issues in System Identification* Stuttgart University, Stuttgart, Germany, September 6 1993.

Lennart Ljung: *A Role of Different Assumptions in Noise Models*, ERNSI Meeting in Louvain-la-Neuve, September 29, 1993.

Håkan Hjalmarsson: *Optimality and Robustness in Parameter Estimation* PAI/IUAP-17 Network on Systems and Control. Study Day in Louvain-la-Neuve, September 24 1993.

Predrag Pucar: *Segmentation of Laser Images using System Identification Techniques* ERNSI Meeting in Louvain-la-Neuve, September 30, 1993.

Tomas McKelvey: *Fully Parameterized State-Space Models in System Identification.* Second workshop of ERNSI in Louvain-la-Neuve,Belgium, September 30, 1993.

Jan-Erik Strömberg: *The conceptual side of mode switching*, the IEEE International Conference on Systems, Man and Cybernetics, Le Touquet, France, October 17, 1993.

Lennart Ljung: *A Perspective of System Identification*,Plenary Address, The MatLab Conference, Cambridge, Massachusetts, USA, October 18, 1993.

Fredrik Gustafsson: *Estimation of tire-road friction*, Uppsala University, Uppsala, Sweden, October 20, 1993.

Svante Gunnarsson: *Frequency domain performance measures in recursive identification.* Université Catholique de Louvain, Louvain-la-Neuve, Belgium, October 1993.

Anders Helmersson: *Lyapunov Technique for Assuring Global Performance Bound*, the Lund Institute of Technology, Lund, Sweden, October 22, 1993.

Fredrik Gustafsson: *Kalman filtering*, SAAB, Linköping, Sweden, October 27, 1993.

Fredrik Gustafsson: *Using MATLAB for tire-road friction estimation*, Comsol, Stockholm, Sweden, October 28, 1993.

Fredrik Gustafsson: *Using MATLAB for tire-road friction estimation*, Comsol, Linköping, Sweden, December 8, 1993.

Håkan Hjalmarsson: *Model Quality Issues in System Identification* University of Louvain, Louvain-la-Neuve,Belgium, November 16 1993.

Lennart Ljung: *Information Contents in Identification Data from Closed Loop Operation*, 32nd IEEE Conference on Decision and Control, San Antonio, Texas, USA, December 15, 1993.

Krister Forsman: *Polycon – Computer Algebra Software for Polynomial Control Systems*, 32nd Conference on Decision and Control, San Antonio, Texas, USA, December 1993.

Krister Forsman: *Solving the ARE Symbolically*, 32nd Conference on Decision and Control, San Antonio, Texas, USA, December 1993.

Krister Forsman: *Towards a Mathematical Analysis of Fuzzy Controllers*, 32nd Conference on Decision and Control, San Antonio, Texas, USA, December 1993.

Inger Klein: *Automatic Creation of Sequential Control Schemes in Polynomial Time*, 32nd IEEE Conference on Decision and Control, San Antonio, Texas, USA, December 15, 1993.

Håkan Hjalmarsson: *A Discussion of "Unknown-But-Bounded" Disturbances in System Identification* 32nd Conference on Decision and Control, San Antonio, Texas,USA, December 15, 1993

Lennart Ljung: *Some Results on Identification of Linear Systems Using Frequency Domain Data*, 32nd IEEE Conference on Decision and Control, San Antonio, Texas, USA, December 16, 1993.

Håkan Hjalmarsson: *Asymptotic Correct Correlation Tests* 32nd Conference on Decision and Control, San Antonio, Texas, USA, December 16, 1993

Jan-Erik Strömberg: *Modular modelling of hybrid systems*, Reglerteknik, Chalmers Tekniska Högskola, Göteborg, Sweden, January 21, 1994.

Lennart Ljung: *From Data to Model: A Guided Tour*, Plenary Address, Control'94, IEE Conference on Control, Warwick, United Kingdom, March 22, 1994.

Håkan Hjalmarsson: *A Convergent Iterative Restricted Complexity Control Design Scheme* PAI/IUAP-17 Network on Systems and Control. Study Day in Louvain-la-Neuve, March 30, 1994.

Håkan Hjalmarsson: *A Convergent Iterative Restricted Complexity Control*

Design Scheme Delft University,The Netherlands, March 29, 1994.

Håkan Hjalmarsson: *A Convergent Iterative Restricted Complexity Control Design Scheme* Royal Institute, Stockholm, Sweden, April 7, 1994

Fredrik Gustafsson: *Tire-road friction estimation*, Newcastle University, Australia, April 12, 1994.

Predrag Pucar: *Three Techniques for State Order Estimation of Hidden Markov Models* LADSEB in Padova, Italy, April 13, 1994.

Predrag Pucar:*Segmentation of Laser Range Radar Images using Hidden Markov Field Models* Department of Electrical Engineering, University of Padova, Italy, April 14, 1994.

Krister Forsman: *On Implicitization*, Department of Mathematics, University of Groningen, Groningen, The Netherlands, May 19, 1994.

Krister Forsman: *Hybrid Systems - An Algebraic Approach*, Department of Mathematics, University of Groningen, Groningen, The Netherlands, May 26, 1994.

Krister Forsman: *On Nonlinear Systems with Linear Dynamics*, Eindhoven Technical University, Department of Mathematics and Computing Science, Eindhoven, The Netherlands, May 30, 1994.

Jan-Erik Strömberg: *On discrete and hybrid representation of hybrid systems*, the European Simulation Multiconference, Barcelona, Spain, June 1, 1994.

Jan-Erik Strömberg: *FuzzyCAT – A tool for mathematical analysis of fuzzy controllers*, the European Simulation Multiconference, Barcelona, Spain, June 1, 1994.

Jonas Sjöberg: *Modelling Non-linear Behavior with Neural Network*, International Symposium on Forcasting, June 12-15, Stockholm, Sweden.

Anders Helmersson: *Lyapunov Technique for Assuring Global Performance Bounds* ACC 1995, Baltimore, Maryland, USA, June 29, 1994.

Håkan Hjalmarsson: *Detecting Asymptotically Vanishing Model Uncertainty* 12th IFAC World Congress, Sydney, Australia, July 20, 1993

Håkan Hjalmarsson: *A Model Variance Estimator* 12th IFAC World Congress, Sydney, Australia, July 22, 1993.

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Appendix H

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Appendix I

Master Theses (Examensarbeten)

[116] C. Vahlberg. Direction-finding of broad-band singal-sources with data from a passive sonar-array. Masters Thesis LiTH-ISY-EX-1276, Dept of EE, Linköping University.

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[119] H.G Grubeck. Fuzzy controller design for bwr feedwater control. Masters Thesis LiTH-ISY-EX-1312, Dept of EE, Linköping University.

[120] M. Hultin. Wavelet based filtering of noisy data. Masters Thesis LiTH-ISY-EX-1313, Dept of EE, Linköping University.

[121] L. Fredlund. Nonlinear PID-controllers. Masters Thesis LiTH-ISY-EX-1324, Dept of EE, Linköping University.

[122] G. Nordin. Wavelet based filtering of noisy data in matlab. Masters Thesis LiTH-ISY-EX-1327, Dept of EE, Linköping University.

[123] L. Larm. Pole placement for high order systems with pid controllers - an implementation. Masters Thesis LiTH-ISY-EX-1337, Dept of EE, Linköping University.

[124] P. Larsson. Maple environment for control design. Masters Thesis LiTH-ISY-EX-12, Dept of EE, Linköping University.

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[126] S. Sjögren. Design of an autopilot for a non linear missile using a neural network. Masters Thesis LiTH-ISY-EX-1344, Dept of EE, Linköping University.

[127] P. Olsson. SignSim: A system for realtime simulation of radarsignals from level sensors. Masters Thesis LiTH-ISY-EX-1350, Dept of EE, Linköping University.

[128] M. Lewerth. Parameter identification after transient test, strategies applied to an aircraft model. Masters Thesis LiTH-ISY-EX-1353, Dept of EE, Linköping University.

[129] S. Larsson. Thickness deviation control in cold rolling mills. Masters Thesis LiTH-ISY-EX-1359, Dept of EE, Linköping University.

[130] G. Hägglund and P-O Högnelid. Load prediction in cellular mobile telecommunication networks. Masters Thesis LiTH-ISY-EX-1363, Dept of EE, Linköping University.

[131] M. Sundstedt. Estimation of attitude angle of an autonomous miniature helicopter with on-board sensors. Masters Thesis LiTH-ISY-EX-1367, Dept of EE, Linköping University.

[132] S. Nilsson. Evaluation of two control strategies for a CSTR biogas reactor. Masters Thesis LiTH-ISY-EX-1375, Dept of EE, Linköping University.

[133] S. Axelsson. Dynamic ranking and allocation of radio resources - a study of fuzzy logic. Masters Thesis LiTH-ISY-EX-1383, Dept of EE, Linköping University.

[134] D. Eriksson. Optimization of the program for ima 600, a machine for pattern plating. Masters Thesis LiTH-ISY-EX-1393, Dept of EE, Linköping University.

[135] A. Peterson. Modelling of ship dynamics to predict angles of attitude. Masters Thesis LiTH-ISY-EX-1394, Dept of EE, Linköping University.

[136] J. Andersson. Development of internal testsoftware for the intercare system. Masters Thesis LiTH-ISY-EX-1397, Dept of EE, Linköping University.

[137] J. Håkegård. Modelling of an industrial process suitable for automatic planning. Masters Thesis LiTH-ISY-EX-1400, Dept of EE, Linköping University.

[138] K. Edström. Geometrical interpretation of algebraic observability. Masters Thesis LiTH-ISY-EX-1405, Dept of EE, Linköping University.

[139] T. Erlandsson. Modelling of carton machine with neural networks. Masters Thesis LiTH-ISY-EX-1406, Dept of EE, Linköping University.

[140] T. Jämte. Spatial sound predictions for active noise control. Masters Thesis LiTH-ISY-EX-1408, Dept of EE, Linköping University.

[141] L. Persson. Hardware architecture for control of an autonomous miniature helicopter. Masters Thesis LiTH-ISY-EX-1411, Dept of EE, Linköping University.

[142] C. Kumpalainen. A study of rope load oscillations during control of mine hoist systems. Masters Thesis LiTH-ISY-EX-1422, Dept of EE, Linköping University.

[143] J. Ahlström. Error estimation in an inertial navigation system integrated with some other navigation systems. Masters Thesis LiTH-ISY-EX-1424, Dept of EE, Linköping University.

[144] P. Gotenstam. A study of terrain following and terrain avoidance for aircrafts. Masters Thesis LiTH-ISY-EX-1428, Dept of EE, Linköping University.

[145] M. Jirstrand. Differential algebraic systems theory - some finiteness problems. Masters Thesis LiTH-ISY-EX-1434, Dept of EE, Linköping University.

[146] H. Karlsson. Integration of ir-camera and terrain reference navigation system for visual estimation of ground target position. Masters Thesis LiTH-ISY-EX-1434, Dept of EE, Linköping University.

[147] L. Huge. Modeling for adaptive radioresource allocation. Masters Thesis LiTH-ISY-EX-1443, Dept of EE, Linköping University.

[148] K. Johansson. Analysis and integration of data from simulator. Masters Thesis LiTH-ISY-EX-1446, Dept of EE, Linköping University.