LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT 1994/95

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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.

The year has been filled with various preparations for new research initiatives, relating to new funding forms in Sweden. We have been selected by NUTEK to form 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, Engineering Data Bases and Real Time Systems in the Computer Science Department. The participating companies are ABB Industrial Systems, ABB Robotics, Ericsson Telecom, Mecel AB, SAAB Automobile, SAAB Dynamics and SAAB Military Aircraft. ISIS starts formally on November 1, 1995.

Four of our graduate students have defended their Ph.D. theses during the year: Jan-Erik Strömberg, Ke Wang, Jonas Sjöberg and Tomas McKelvey. Moreover, Peter Lindskog, Jonas Plantin and Johan Gunnarsson finshed their Tekn. Lic. degrees.

Ingegerd Stenlund left us in January to pursue a career as a textile artist. She had then worked as a secretary for the group during exactly 20 years, and we wish her good luck with her new endeavor.

Another noteworthy event during the year was that Mille Millnert was promoted to *Biträdande professor*.

In the following pages the main research results obtained during the academic year 1994/95 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 invite you to visit our home page:

`http:// www.control.isy.liu.se`

This is also the easiest way of accessing most of our reports.

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 secretary 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:

```
ftp.control.isy.liu.se (130.236.24.100)
```

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:

```
http://www.control.isy.liu.se
```

[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.

When you surf around in our WWW-environment you will find some general information over this group, the staff, seminars, 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 group's work, just click and collect.

Our WWW service is always 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: Annual Summer Courses

Since 1983 we have regularly arranged one-week summer courses for our Ph.D.-students with internationally well known lecturers. The courses are open also to participants from other universities and from industry.

We have tried to pick quite recent subjects, where no established literature exists.

Here follows the list of courses, arranged so far:

1983, Optimal Linear Feedback Systems

Lecturer: Bruce Francis, University of Toronto, Toronto, Canada.

The basic theory and techniques of H_∞ optimization for linear systems was presented. In particular the problem of finding a controller minimizing the sensitivity function was considered. The tradeoff between different control objectives were discussed.

1984, Robust Controllers

Lecturer: Michael G Safonov, University of Southern California, Los Angeles, CA.

Fundamental robustness concepts like sector conditions were discussed. The structure of of the robustness problem with plant uncertainties was introduced as well as mathematical tools like singular values. These tools were then used to obtain design methods for controllers.

1985, Nonlinear Estimation

Lecturer: Tomas Björk, Royal Institute of Technology, Stockholm, Sweden.

The basic estimation problem for nonlinear differential equations driven by white Gaussian noise was presented. It was shown that the solution of the nonlinear filtering problem was described by the Zakai equation. It was also shown that in general no finite dimensional filter can solve the problem exactly.

1986, Control Issues in Robotics

Lecturer: M. Vidyasagar, Centre for Artificial Intelligence and Robotics, Bangalore, India.

The principles of mechanics that form the basis of modeling in robotics were presented. A systematic framework for description of robots was used to derive kinematic and dynamic models. Various control schemes could then be analyzed in the context of robotics. Methods that were covered include exact linearization (computed torque) and controllers for flexible arms and elastic joints.

1987, Numerical and Symbolic Signal Processing

Lecturer: Albert Benveniste, IRISA, Rennes, France.

The basic problems of numeric/symbolic signal processing were introduced by examples of speech recognition systems. Then dynamical models for discrete event signal processing were described. The system theory of dynamic/symbolic signal processing was exposed. Histories, signals and clocks were discussed as well as clock calculus, calculation of dependencies, transition systems and automata.

1988, Discrete Event Systems

Lecturer: Peter Ramage, Princeton University, Princeton, N.J..

The history of discrete event systems methodology was discussed. Various types of models like logical, algebraic, deterministic timed and stochastic ones were exemplified. A theory of controllability of sequences was developed and analyzed. The coordination of product systems could then be discussed. The

complexity of some coordination problems, for instance mutual exclusion was analyzed.

1990, Differential Algebra and Nonlinear Control

Lecturer: Michel Fliess, Lab. des Signaux et Systemes, Gif-sur-Yvette, France.

The course described the basic concepts of differential fields. From this background dynamic systems could be defined abstractly. With the introduction of transcendence degree, invertibilty of systems could be discussed. Concepts like observability and controllability were also treated in a differential algebraic framework. The discrete time case and difference algebra were mentioned.

1992, Digital Neural Networks

Lecturer: S. Y. Kung, Princeton University, Princeton, N.J..

The classification of neural networks into fixed, unsupervised and supervised ones was introduced. Various concrete examples, like Hopfield nets, competitive learning and Adaline were analyzed. Connections between neural computing and hidden Markov models were stressed. Various implementation aspects were also covered.

1993, Optimal and Suboptimal Techniques for Sensor Array Processing

Lecturer: Mats Viberg, Chalmers Institute of Technology, Göteborg, Sweden.

The problem of sensor array processing and its various applications were described. The models and their assumptions were described and used to investigate the various sensor array processing techniques. Maximum likelihood estimation, beam-forming and eigenstructure based methods were discussed.

1994, Modeling techniques

Lecturer: Henry Paynter, MIT, Cambridge, MA.

The historical development of bond graphs and similar energy flow based concepts was described. It was shown how the fundamental concepts in electromagnetic filed theory could be applied to concrete modeling problems for rotating electrical machinery.

1995, Convex optimization

Lecturer: Stephen Boyd, Stanford University, Stanford, CA.

The family of convex optimization problems was defined. Many engineering applications, in particular with control implications were pointed out. Algorithms were also thoroughly discussed.

Chapter 4

System Identification

4.1 Introduction

The research in System Identification covers a rather wide spectrum, from general principles to particular applications. Together with IRISA at Rennes, we have taken a broader interest in non-linear black box models, such as Neural Networks, Hinging Hyperplanes and Fuzzy Modeling – See Section 4.5. The Ph.d.-thesis by Jonas Sjöberg, [4], deals with that area.

Tomas McKelvey also finished his Ph.D.-thesis, [3], in the System Identification area, with results on state-space models and frequency domain methods. See Sections 4.6 and 4.7 for more information.

Some general expositions about the system identification problem include [71], [123] and [145].

4.2 Model structure selection

Classical approaches to determine a suitable model structure from observed input-output data are based on hypothesis tests and information based criteria. Recently, the model structure has been considered as a stochastic variable and standard estimation techniques have been proposed. The resulting estimators are closely related to the aforementioned methods. However, it turns out that there are a number of prior choices in the problem formulation, which are crucial for the estimators' behavior.

In the *Automatica* paper [18], the role of the prior choices was clarified. This was done in a linear regression framework. In short, the contribution is as follows. There are two unknown nuisance parameters: the model parameters and the noise variance. There are several possibilities concerning the prior assumptions.

- The parameter vector can be considered known, estimated simultaneously with the model structure or the parameters can be assigned a prior that is either flat or Gaussian.

- The noise variance can be considered known, estimated simultaneously with the model structure or the noise variance can be assigned a prior that is either flat, inversely Wishart distributed or Jeffrey's.

These assumptions all lead to an explicit likelihood function and there are totally 20 different combinations. Methods considered in the literature all correspond to special cases of these combinations. The asymptotic properties have been analyzed. Briefly, the result is that all combinations with a prior on the parameters will give a correct estimate of the model structure for a large enough number of data.

For auto-regressive models, we also investigated a novel prior assumption on stability and derived a 21'th ML estimator for the model order and also an estimator for the parameters themselves. An advantage here is that the estimated model is always stable due to the novel prior. The analysis was done in a lattice filter framework.

4.3 Composite modeling

A problem considered in the *IEEE Transactions on Automatic Control* paper [19] is how to estimate the frequency function of a system and the associated estimation error when a set of possible model structures is given and when one of them is known to contain the true system. The "classical" solution to this problem is to, firstly, use a consistent model structure selection criterion to discard all but one single structure. Secondly, estimate a model in this structure and, thirdly, conditioned on the assumption that the chosen structure contains the true system, compute an estimate of the estimation error. However, for a finite data set one cannot guarantee that the correct structure is chosen and this "structural" uncertainty is lost in the previously mentioned approach. In this contribution a method is developed that combines the frequency function estimates and the estimation errors from all possible structures into a joint estimate and estimation error. Hence, this approach by-passes the structure selection problem. This is accomplished by employing a Bayesian setting. Special attention is given to the choice of priors. With this approach it is possible to benefit from a priori information about the frequency function even though the model structure is unknown.

4.4 Orthonormal bases for system identification

In the conference paper [57] we developed a general and very simple construction for complete orthonormal bases for system identification:

$$\mathcal{B}_n(z) = \frac{\sqrt{1-a_n^2}}{z+a_n} \prod_{k=0}^{n-1} \frac{1+a_k z}{z+a_k}$$

It was shown that these basis function would be the result if a Gram-Schmidt orthonormalization procedure is applied to first order AR models with poles in a_n.

These functions are used to build up the transfer function of a dynamic system in the following way:

$$y(t) = \sum_{k=0}^{\infty} \left(\theta_k \mathcal{B}_k(q^{-1})\right) u(t) + e(t) \tag{4.1}$$

The estimation of the parameters of a truncated model approximation is a standard least squares problem, which here is very well-conditioned due to orthonormality. The choice of poles a_n in the construction is related to prior knowledge of the system and what properties of the system we want to capture.

Consider the impulse response of the the basis functions. Orthonormality means by definition that

$$\sum_{n=1}^{\infty} b_k(n) b_l(n) = \delta_{k-l}$$

We have proven that our construction generates a complete set. That is, any stable transfer function can be approximated arbitrarily well. Completeness can be shown to be equivalent to

$$\sum_{k=1}^{\infty} b_k(m) b_k(n) = \delta_{m-n},$$

which shows a nice duality between time and basis order.

Our construction provides a unifying formulation of all known orthonormal bases since the common FIR and recently popular Laguerre and Kautz model structures are restrictive special cases of our construction as is another construction method based on balanced realizations for all-pass functions.

However, in contrast to these special cases, the basis vectors in our unifying construction can have nearly arbitrary magnitude frequency response according to the prior information the user wishes to inject into the problem. We provide results characterizing the completeness of our bases, and the accuracy properties of models estimated using our bases.

Current research aims at getting expressions for the bias error and asymptotic variance for the transfer function estimate.

4.5 Nonlinear Model Structures

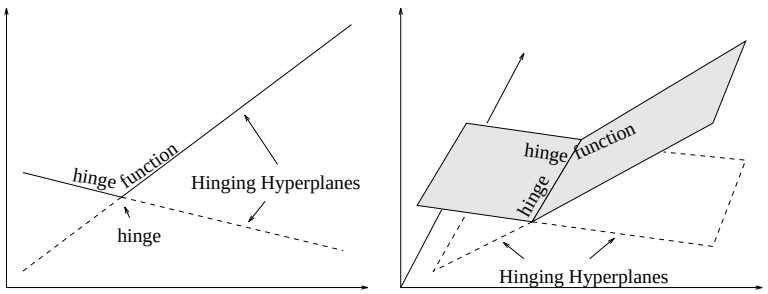
Nonlinear system identification is difficult because a nonlinear system can be nonlinear in so many different ways. Traditionally, only model structures with constrained nonlinearities have had success in practice like Hammerstein and Wiener models.

Lately a number of new model structures have been proposed and shown to be useful in applications. Most interest has been focused on artificial neural networks. Other models structures are, *e.g*, wavelets and hinging hyperplanes. All these new model structures are described in a common mathematical frame-work in two companion papers, [11, 12]. Function fitting in spaces of several dimension is in general a hard problem which is called the *curse of dimensionality*. The discussed model structures deal with this problem in different ways. Neural nets, hinging hyperplanes and projection pursuit can be described as projecting the data onto subspaces of lower dimensions. With a wavelet or a radial basis models one can use a constructive estimation algorithm to choose the positions of the basis functions. This gives model structures with less parameters which can be expected to improve the performance of the model.

The first one of the companion papers, [11], takes the user's perspective, gives an overview of nonlinear identification and focuses on the choices the user has to make. The second paper [12] concentrates on the mathematical foundation of these different model structures. Both of these papers are also electronically available as technical reports, [130, 131]

Hinging Hyperplanes (HH) models have recently been suggested as nonlinear black-box model structure. They can be described as sums of hinge functions, depicted in Figure 4.1.

In [109] HH models are considered for identification of dynamical systems and some examples on real data are investigated. When HH models were first introduced a special estimation algorithm was suggested. In [113] it is shown that this algorithm is just a special case of a Newton algorithm. The paper also discusses a number of topics related to the estimation in HH models.



(a) 2-Dimensional (b) 3-Dimensional

Figure 4.1: Hinge, hinging hyperplane and hinge function

4.6 State Space Models

Models in state-space form is a model structure particularly convenient when modeling 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 [28] 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. The existing subspace algorithms all share a common deficiency; they are not consistent when identifying systems operating in closed loop. In [139] the reason for this is pointed out by focusing on the estimated k-step ahead predictors. By recomputing these from a "non-parametric" one-step ahead predictor model, closed loop data can be handled. If the input signal is periodic, a subspace based algorithm can be formulated [16, 89, 147, 3, 40] which has an extremely low computational complexity but is also consistent under weak assumptions on the measurement noise.

4.7 Frequency Domain Methods

The time domain subspace identification methods can also be formulated in the frequency domain. As primary data these methods use samples of the frequency response function of the system. In [49, 47, 3] 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. The resulting estimate is a stochastic variable and in [152] it is shown that it is asymptotically normal distributed and an analytic expression of the variance is derived. Frequency weightings can be introduced in the algorithm and the connection with frequency balanced truncation is investigated in [154]. In [88, 14] the algorithm is analyzed under the assumption that the true system is infinite dimensional and it is shown that the estimate converges to the truncated balanced realization.

4.8 Model Validation

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. Another approach is to introduce *regularization*, i.e., to modify the criterion by an additional penalty for large parameter values

$$W_N(\theta) = \sum \varepsilon^2 + \delta|\theta|^2 \tag{4.2}$$

then the variance-bias trade-off can be done by the choice of δ.

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 4.2. This is described in detail in [13] and [31].

Where should this 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 have been, partly, used in the estimation and, hence, one caution has to be taken if these data are also used as validation data.

Assessing the size of the total error between an estimated model and the true system is clearly of great importance. Traditionally, measures have been based on the variance error only. In [53] and [77] it is shown how "classical" model validation tests, in terms of cross-correlation functions between resid-

uals and past inputs, give explicit expressions for the discrepancy between the estimated and the true frequency functions.

A result on how to formulate the correlation tests is given in [100]. How to estimate the variance of a model, even in the presence of bias error is described in [104]. Minimizing the variance error by a proper choice of norm in the identification criterion is discussed in [101].

A unified view on the disturbances acting on systems is given in [102], and geometrical arguments for model validation are discussed in [150].

4.9 Recursive Identification

Consider the standard problem of estimating the time-varying parameters $\theta(t)$ of a linear regression:

$$y(t) = \varphi^T(t)\theta(t) + e(t) \tag{4.3}$$

The basic algorithm for this is

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

To get proper guidelines for choosing the design variables μ and $K(t)$ it is necessary to have lucid expressions for the tracking error $\hat{\theta}(t) - \theta(t)$. In [9] exponential stability of the basic algorithm is established under very general conditions. Given stability, it is then the task to find useful expressions for the size of the error. Such expressions are given in [10].

The so called LMS case, where $K(t)$ is chosen as $\varphi(t)$ in the basic algorithm, combined with structural detection, is discussed in [118] and [58].

"Accelerated convergence" is a way of obtaining optimal asymptotic properties of the estimate (for the constant parameter case) by running the LMS algorithm, followed by a second round of averaging. This scheme is analyzed in [50].

The basic linear regression expression (4.3) also covers the time-series case, for modeling AR-processes. The the recursive identifier can be seen as a way of tracking a "time-varying spectrum". In [51, 105] it is discussed how to choose $K(t)$ in this case, so that different tracking rates are achieved in different frequency ranges. The compromise between time resolution and frequency resolution can then be made in a rational manner.

Regularization issues related to the basic recursive algorithm are discussed in [37] and several issues around the numerical implementation of the least squares algorithm are treated in [106, 107, 108].

4.10 Identification and Controller Design

Iterative methods for tuning of controllers have been studied by several research groups during the last years. While these methods typically have included an identification step more recent research has concentrated on a method where the controller parameters are updated directly. The main results from this work deal with a scheme where the controller parameters ρ are updated 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 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. A complete presentation of the idea is given in [87], while a more condensed description is given in [54]. Some relationships between this direct controller tuning and the methods combining identification and controller design are discussed in [59] and [72]. In [55] some possible benefits of carrying out identification in closed loop are investigated.

The method has been tested in both simulations and in applications to laboratory scale processes, and the results are presented in [143] and [115]. The results in [143] is one contribution to a benchmark problem to be presented at the 1995 European Control Conference. In [90], which also will appear at 1995 ECC, it is discussed how the method will perform when it is applied to linear time-varying system.

4.11 Applications

During the year some industrial applications of different identification techniques have been reported. The applications range from vibration analysis in aerospace industry, as reported in [23, 48] and [151] to estimation of residence time in a paper pulp process, discussed in [30]. In [27] it is discussed how the

inter-sampling behavior of real data can be modeled and how this effects the identification result. The paper [29] presents tools for semi-physical modeling. The report [129] gives a comparison between semi-physical modeling and black-box modeling with neural nets. Advantages and disadvantages with the different modeling approaches are discussed and applied to a case study. It is also pointed out how the methods can be combined to give more information about the system. In [69] three different real systems are are identified with neural nets.

Chapter 5

Signal Processing

The group's activity in the signal processing field, is reported in this chapter. The work on time-frequency analysis is done by Mille Millnert. The section on signal processing in communication, change detection and the section on forward-backward filtering, is written by Fredrik Gustafsson. The problem of power control to mitigate Rayleigh fading is studied by Anders Ericsson.

5.1 Time-Frequency Analysis for vibrometry

Coherent laser radar (CLR) systems have been investigated over several decades primarily for military applications. In order to receive a more general industrial acceptance, compact, robust, cost-effective systems and more general signal processing tools must be developed. This work is a collaboration with Ingmar Renhorn, et al, at FOA3 Linköping and focuses on signal processing problems related to laser radar systems.

Homodyne Detection

A vibrating surface will generate a detectable Doppler shift in the received laser signal. The instantaneous frequency is determined by the vibrational frequency and vibrational amplitude of the surface. If the position of the surface is given by $x(t)$, a harmonic description apart from a phase factor is

$$x(t) = x_0 \sin(\omega_v t) \tag{5.1}$$

where $\omega_v = 2\pi f_v$, f_v is the vibrational frequency and x_0 is the vibrational amplitude. The instantaneous Doppler shift is given by

$$v_v(t) = \frac{2}{\lambda}\frac{dx(t)}{dt} \tag{5.2}$$

$$v_v(t) = v_D(t)\cos(2\pi f_v t) \tag{5.3}$$

$$v_D(t) = \frac{4\pi x_0 f_v}{\lambda} \tag{5.4}$$

For a moving target, a constant frequency shift will be superimposed on the vibrationally induced Doppler shift. The traditional signal processing method is to use an FM-detector that is optimized for the relevant signal. This method works well at large signal-to-noise ratios (S/N $>$ 10 dB). In many applications, the S/N will be low, at least occasionally, due to speckles. A more robust signal processing technique that will allow also low S/N ratios is therefore desirable.

The instantaneous frequency is given by the Doppler shift from the radial velocity of the target and the (usually much smaller) Doppler shift induced by the vibrating surface. The signal can, for a harmonic vibration, be described by

$$s(t) \approx C\cos(2\pi v_c t + \mu\sin(2\pi f_v t + \theta_v) + \theta) \tag{5.5}$$

where μ is the modulation index and the vibration is periodic with the frequency f_n. A signal model consisting of signal components is given by

$$y(t) = \sum_{n=1}^{n_s} s_n(t) + e(t) \tag{5.6}$$

The signal components are given by

$$s_n(t) = C_n\cos(\omega_c^{(n)}t + \mu_n\sin(\omega_v^{(n)}t + \theta_v^{(n)}) + \theta_c^{(n)} \tag{5.7}$$

where the parameters $\begin{pmatrix} C_n & \omega_c^{(n)} & \mu_n & \theta_v^{(n)} \end{pmatrix}$ for the signal components are to be estimated.

The estimation method is based on time-frequency analysis using the short time Fourier transform. In Fig. 5.2 the spectrogram of the signal is shown.

The fundamental problem of the parameter estimation is to separate the two signal components. The modulation frequency of each signal component gives a sinusoidal "ridge" in the spectrogram of the form

$$\omega_v^{(n)}\mu_n\sin(\omega_v^{(n)}t + \theta_v^{(n)}) \tag{5.8}$$

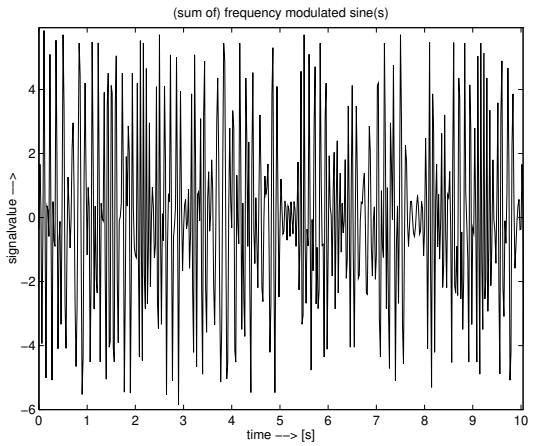


Figure 5.1: A vibrometry signal with two signal components.

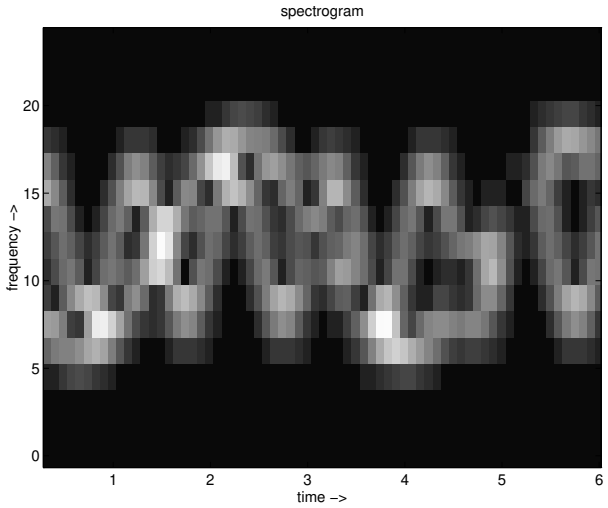


Figure 5.2: The spectrogram of the signal in Fig. 5.1 based on a 32-sample FFT using a Hamming window.

i.e., a sinusoid with frequency $\omega_v^{(n)}$ and amplitude $\omega_v^{(n)}\mu_n$. Component separation can be based on the mean frequency of the spectra for each time slot in the spectrogram, i.e.,

$$\bar{\omega}(t) = \frac{\sum_{\omega>0} |Y(\omega,t)|^2 \omega}{\sum_{\omega>0} |Y(\omega,t)|^2} \tag{5.9}$$

In Fig. 5.3 the resulting signal is shown.

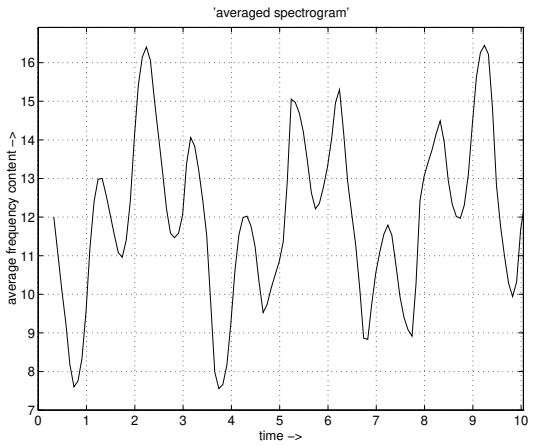


Figure 5.3: The mean frequency of the spectrogram in Fig. 5.2.

By fitting the models (5.6) to the spectrogram in such a way that the accumulated energy of the corresponding time-frequency bins is maximized the signal parameters can be estimated. In Table 5.1 the correct and estimated values of the signal parameters. For more information see [67] or [146].

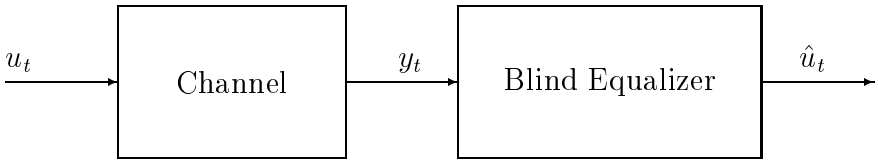
		$\omega_v^{(n)}$	μ_n	$\theta_v^{(n)}$	C_n
signal 1	true values	0.3	20	1.885	2.7
	estimated values	0.300	18.17	1.950	2.45
signal 2	true values	1	4.3	4.712	3.3
	estimated values	1.001	3.00	4.653	3.22

Table 5.1: The correct and estimated values of the parameters in the signal model. The definition of the quantities in the heading of the table is found in (5.7)

5.2 Signal processing in communication

Blind equalization

Consider the following communication system:



The blind equalization problem consists in *recovering the transmitted signal from the received output sequence only.*

In a paper published in *IEEE Transactions on Communication* [17] two results were presented. The first one is concerned with the identifiability question. This is a fundamental result about whether the problem is solvable for any blind equalizer. This is principally different from the *admissibility* question that is discussed in literature, which concerns only the question of convergence of a specific algorithm.

Assume $u_t \in \{\pm 1, \pm 3, ..., \pm(M-1)\}$. The basic result is the following: *Necessary condition for identifiability:*

- $\{u_t\}$ is *persistently exciting* (PE) of order $2n-1$.

Sufficient conditions for identifiability:

- $\{u_t\}$ is PE of order $2n-1$.
- The system parameters $\{b_i\}$ are linearly independent over a (known) finite set of integers

Compare this result with a well-known theorem in system identification. For a *known input signal*, a necessary and sufficient condition for identifiability is

- $\{u_t\}$ is PE of order n at time t

The condition on the system means that identifiability might fail when there exist relationships like

$$3b_1 + 7b_3 = 0$$

The sufficient condition has turned out to be conservative in practice and mostly the necessary condition is also sufficient.

The second result in the paper is an algorithm consisting of a bank of Kalman filters. These are matched to specific input sequences and an approximate maximum likelihood estimate of the input sequence and channel parameters is computed. This is in the spirit of the well-known Viterbi algorithm (which can be applied if a channel model is already known) and no explicit inverse of the channel dynamics has to be formed in the equalizer. The algorithm was illustrated on a mobile telephone channel with Rayleigh fading.

Echo detection

In the conference papers [58, 118] the following problem was considered. Assume a FIR signal model

$$y(t) = \sum_{i=1}^{n} \theta(k_i) u(t - k_i) + e(t) = \varphi^T(t)\theta + e(t)$$

where we have the following implicit assumption: *The number of possible parameters* $d = \dim\theta$ *is much larger (e.g.* $d > 100$*) than the number of active taps* n *(e.g.* $n < 10$*).* This assumption is relevant for circuit echo paths in four-wire telephone communication.

That is, most of the impulse response coefficients are known to be 0. The standard approach is to apply the LMS algorithm and estimate all coefficients. We propose to compute the maximum likelihood estimate of the active coefficients in a first step. Then the RLS estimate of these parameters is computed. In this way, the estimated channel model converges faster and the prediction error variance will decrease. To overcome the computational burden in the ML estimator, we derived a logical approximation based on an assumption on whiteness of the input. The total complexity of the algorithm is comparable to LMS applied to the fully parameterized model.

Detection of echo path changes and double talk.

The problem of detection and discrimination of double talk and change in the echo path in a telephone channel is considered in a forthcoming report (LiTH-ISY-R-1790) This is a relevant problem in four-wire telephone communication, where a very annoying delayed version of your own speech can be heard in your telephone, if no filtering is applied. This problem is usually solved by an adaptive filter.

A change in echo path requires fast adaptation of the channel model to be able to equalize the echo dynamics. On the other hand, the adaptation rate should be reduced when double talk (both are talking at the same time)

occurs. Thus, it is critical to quickly detect a change in echo path while not confusing it with double talk, which gives a similar effect. The proposed likelihood based approach compares a global channel model with a local one over a sliding window, both estimated with the Recursive Least Squares algorithm, and the two critical events are detected and discriminated.

5.3 Change detection

The *generalized likelihood ratio* (GLR) test is a widely used method for detecting abrupt changes in linear systems and signals. It is based on the following standard state space model

$$\begin{aligned} x_{t+1} &= F_t x_t + G_t u_t + w_t + \delta(k-t)\nu \\ y_t &= H_t x_t + e_t. \end{aligned}$$

where a state jump ν occurs at time k. In an *IEEE Transactions on Automatic Control* [20] paper, the *marginalized likelihood ratio* (MLR) test is introduced for eliminating three shortcomings of GLR, while preserving its applicability and generality.

1. The need for a user-chosen threshold is eliminated in MLR.

2. The noise levels need not be known exactly and may even change over time, which means that MLR is robust.

3. A very efficient exact implementation with linear in time complexity for batch-wise data processing is developed, which corresponds to running one Kalman filter forwards and a second one backwards in time. This should be compared to the quadratic in time complexity of the exact GLR.

The reduction in the number of design parameters makes MLR very easy to apply. The powerful off-line two filter implementation should further facilitate the design of change detectors based on Monte Carlo simulations.

5.4 Friction estimation in cars

The final report of a joint project between AB Volvo and Automatic Control, Linköping University is presented in [142]. The Automatic Control group was responsible for all algorithm development, construction of hardware for a prototype and test trials. The algorithm includes Kalman filtering, change detection, outlier rejection and errors in variables compensation.

This work has been a part of the project *Driver Assistance and Local Traffic Management* in the Swedish RTI program '91-'94. Main sponsors have been The Swedish Board for Industrial and Technical Development, AB Volvo, Saab-Scania AB and The Swedish National Road Administration.

5.5 Forward-backward filtering

Forward-backward filtering is a common tool in off-line filtering for implementing non-causal filters. Filtering first forwards and then backwards or the other way around does not give the same result generally. In [22], [85] we propose a method to choose the initial state to obtain uniqueness and to remove transients at both ends.

A zero-phase filter can be obtained from any stable filter $G(q)$ using $y(t) = |G(q)|^2 u(t) = G(q^{-1})G(q)u(t)$. Here $G(q^{-1})$ must be implemented backwards in time to be stable. This is for instance done in Matlab's **filtfilt** function. Depending on in which order we apply $G(q)$ and $G(q^{-1})$, we get different results. Let us denote the resulting sequences Y_{bf} and Y_{fb}. The uniqueness problem can be solved by implementing the partial fractions of the filter, so we rewrite $|G(q)|^2 = G^+(q) + G^-(q)$. However, this does not solve the problem with transients. What we do is to compute the initial states of the filters to minimize $Y_{fb} - Y_{bf}$.

As an illustration, the first plot in Figure 5.4 shows an EKG signal with a 50 Hz disturbance. A fourth order zero-phase Butterworth stop-band filter with cutoff frequencies 45 and 55 Hz is used to attenuate the disturbance while keeping the shape of the EKG signal. Matlab's `filtfilt` function is used to demonstrate an *ad-hoc* choice of initial conditions, and the result is shown in the second plot. There is a significant transient at the beginning, and $\|Y_{bf} - Y_{fb}\| = 2.3$. Interestingly, it turns out that the result improves somewhat with zero initial conditions, for which $\|Y_{bf} - Y_{fb}\| = 1.7$. The third plot is obtained with the partial fraction method. Here the transient is less, but on the other hand it appears at both ends. The new method gives a superior result with $\|Y_{bf} - Y_{fb}\| = 6 \cdot 10^{-10}$ and also the best approximation of the true signal, which can be computed exactly by model based methods for this particular example.

5.6 Power control to mitigate the effects of Rayleigh fading

In an urban area, the channels used for mobile telephony are subject to Rayleigh fading due to multipath wave spreading. This will result in varia-

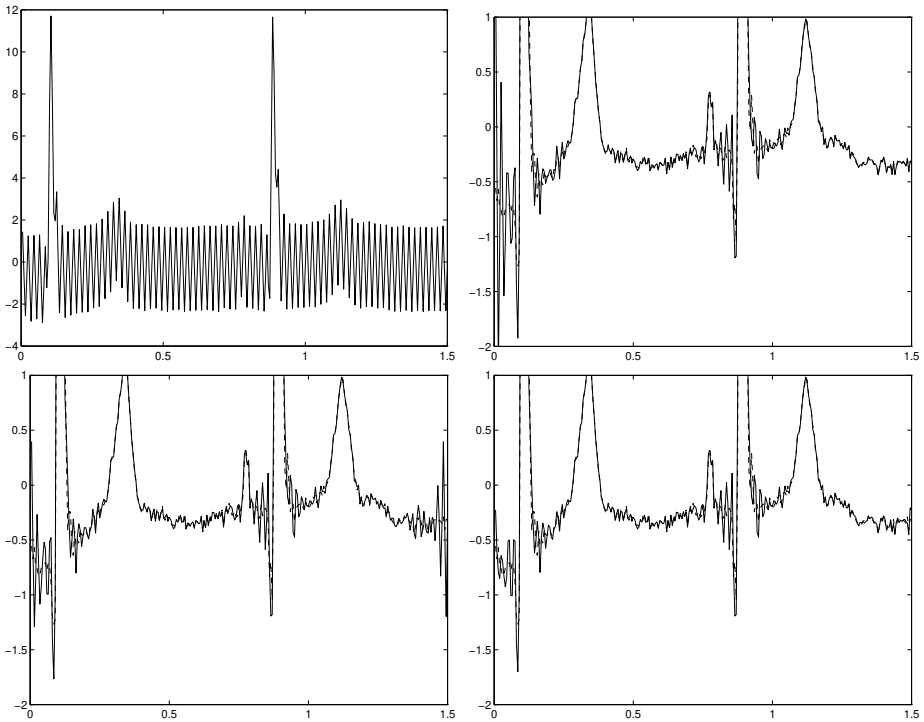


Figure 5.4: An EKG signal with a 50 Hz disturbance (upper left). The signal is filtered through a zero-phase Butterworth filter using Matlab's `filtfilt` (upper right), partial fractions (lower left) and finally using the new method (lower right). Dashed curve shows the true signal in the last three plots.

tions of the quality of the signal (usually measured in C/I - Carrier signal power/Interference signal power) when the mobile moves. For a TDMA system, this may result in that several consecutive TDMA frames are sent during a fade, resulting in an unacceptable low C/I. In, i.e., GSM the usage of frequency hopping, prevents this. For systems that not have this as an option, i.e. ADC, other methods to mitigate these problems must be used. One possible method is to change the transmitting power in the uplink (from mobile to base station) to compensate for the fading effects.

The problem can be divided into two parts: One is to find a power control algorithm which works close to optimal for known future values of the channel, and the other part is to predict these future values with a sufficient accuracy.

The first problem leads, for a small scale example, to a control scheme with two modes: The first mode is to follow a solution giving all mobiles

approximately equal C/I when this is sufficient, and the other is to invoke a Bang-Bang strategy on the control signal (power change).

In the second problem, it turns out that, using the power gain, it is easy to get sufficiently good predictions for the noise free case with simple linear models. However, the predictions are extremely noise sensitive, resulting in poor predictions when the signals are subject to measurement noise.

This project is a collaboration with Ericsson Radio Systems, Kista.

Chapter 6

Non Linear Systems

6.1 Stabilizable regions

One of the most common nonlinearities is an amplitude limit or saturation of a signal. It is almost always present at the input of a system due to the physical limitations of the actuators. It is often combined with other restrictions caused by the dynamic response of the actuators. A simple model that covers many applications is to assume that both the control signal and its derivative are bounded:

$$u_{low} \leq u \leq u_{high}, \quad U_{low} \leq \dot{u} \leq U_{high} \tag{6.1}$$

This means that u has to be regarded as state variable and $\dot{u}$ as the new input. The bounds (6.1) will of course cause a deterioration of the performance of any system, but the consequences will be most severe if the controlled physical system is unstable. This is the case in some aircraft control problems and for certain chemical reactions. If the system is linear apart from (6.1) then it is possible to calculate the stabilizable region in the state space. It is possible to design a feedback law of bang-bang type that stabilizes the system in that region. This is described in [62]. In figure 6.1 the situation is described for a system with one control signal and one unstable eigenvalue. The horisontal axis is a coordinate along the unstable eigenvector and the vertical coordinate the input from the actuator. The stabilizable region is bounded by the horisontal lines through -1 and 1 and by the curves through the points $-1, 1$ and $1, -1$.

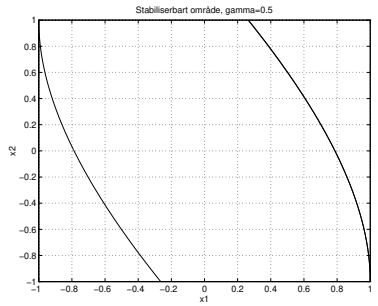


Figure 6.1: Stabilizable region for one unstable eigenvalue

6.2 Normal Forms and Zero Dynamics

The normal form of affine state space systems

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

has been extensively studied during the last decade. For affine SISO systems (6.2) with relative degree r it becomes

$$\begin{aligned} \dot{\zeta}_1 &= \zeta_2 \\ &\vdots \\ \dot{\zeta}_{r-1} &= \xi \\ \dot{\xi} &= b(\zeta, \xi, \eta) + a(\zeta, \xi, \eta)u \\ \dot{\eta}_1 &= q_1(\zeta, \xi, \eta) + p_1(\zeta, \xi, \eta)u \\ &\vdots \\ \dot{\eta}_{n-r} &= q_{n-r}(\zeta, \xi, \eta) + p_{n-r}(\zeta, \xi, \eta)u \\ y &= \zeta_1 \end{aligned} \tag{6.3}$$

The normal form has found several important applications. Two such applications are exact input-output linearization and sliding mode control. A property of affine nonlinear systems that is simple to compute given a normal form is the zero dynamics. The properties of the zero dynamics are important not only in the applications mentioned above but also, for instance, in stabilization. Usually, the analysis of the normal form and the zero dynamics

as well as the computation is done using tools from differential geometry. An outline of a more algebraic approach is given below.

It is shown in [45] how zeros of the sequence of transfer functions

$$H_1(s_1),\ H_2(s_1,s_2),\dots,H_n(s_1,\dots,s_n),\dots \tag{6.4}$$

that emerge from the Laplace transform of the regular kernels in a Volterra series are connected to the zero dynamics. Given a certain bilinear state space system one part of the numerator zeros is exactly equal to the eigenvalues of a linear part of the zero dynamics. For a class of homogenous systems this relation between zeros of the transfer function and the zero dynamics can be seen without computing the bilinear realization. These results can be viewed as generalizations of the linear case where the zeros of the transfer function are exactly the same as the poles of the zero dynamics.

In [46, 63, 116] differential algebra, and in particular the Ritt algorithm, is used for computing the zero dynamics of affine state space systems. The restriction that differential algebra can handle only differential polynomials is removed by utilizing the fact that many smooth functions can be described by polynomial differential equations.

A generalized normal form is considered in [126, 149] for a differential algebraic dynamics. This definition is, as in the affine case, based on the notion of a relative degree, i.e., the minimum order of an output derivative that depends explicitly on the input. Since the differential algebraic definition of a dynamics gives rise to state equations

$$\begin{aligned} A_i\left(\dot{x}_i,x,\bar{u}\right)&=0,\ \ i=1,\dots,n\\ B_j\left(y_j,x,\bar{u}\right)&=0,\ \ j=1,\dots,p \end{aligned} \tag{6.5}$$

some other tool different from differential geometry is needed to compute the relative degree and the normal form. The tool that is used for these computations is Gröbner bases. The generalized normal form then gets the structure

$$\begin{aligned} \dot{\zeta}_1&=\zeta_2\\ &\vdots\\ \dot{\zeta}_{r-1}&=\xi\\ \bar{A}\left(\dot{\xi},\zeta,\xi,\eta,\bar{u}\right)&=0\\ \tilde{A}_1\left(\dot{\eta}_1,\zeta,\xi,\eta,\bar{u}\right)&=0\\ &\vdots\\ \tilde{A}_{n-r}\left(\dot{\eta}_{n-r},\zeta,\xi,\eta,\bar{u}\right)&=0\\ y&=\zeta_1 \end{aligned} \tag{6.6}$$

in the SISO case. The MIMO case is treated in [149]. As expected the normal form (6.3), in the polynomial case, follows from this generalized normal form.

As an application [124, 125] shows how these results can be used for the design of sliding mode control laws. In particular it is shown in [125], that the generalized normal form is useful in this context.

6.3 Symbolic calculations for filtering and control

Many problems in control and signal processing lead to Riccati equations. Standard linear quadratic design leads to algebraic Riccati equations, while more general problems might lead to Riccati differential equations. For many problems it is of interest to calculate solutions symbolically in order to display the structure. In [2] this problem is investigated. It is shown how certain transformations lead to block diagonal and block triangular forms that make symbolic calculations easy. They also make it possible to extend the classical theory of Riccati equations to cover situations with unobservable and/or uncontrollable eigenvalues on the imaginary axis. This is of interest when the system matrices model disturbances which are sinusoidal, which happens for instance in power system applications. One such application, a saturating current transformer, is investigated in [2]. The symbolic representation of the Riccati equation solutions is particularly useful in this case when the ordinary Kalman filter has to be modified into a form of extended Kalman filter.

6.4 Algebraic methods in control

Differential Algebraic Systems Theory

The relations between state space and input output representations play an important role in systems theory. A natural framework for their study is differential algebra and in particular differential ideals. Loosely speaking, a differential ideal is the set of all differential polynomials which can be derived from the differential polynomials originally defining the system. The set of all differential polynomials in the variables $x_1, \ldots, x_n$, i.e., all polynomials in these variables and their derivatives is denoted $k\{x_1, \ldots, x_n\}$.

Given a system of differential polynomials

$$p_1 = 0, \ldots, p_s = 0,$$

the corresponding differential ideal is denoted $\mathcal{I} = [p_1, \ldots, p_s]$. The differential polynomials $p_1, \ldots, p_s$ are called the generators of $\mathcal{I}$. Since there

are a finite number of generators this ideal is called (differentially) finitely generated. It is well known that there are differential ideals which are not finitely generated. However all differential ideals corresponding to a finite set of differential equations are finitely generated by construction.

It can be shown that $\mathcal{J} = \mathcal{I} \cap k\{x_r, \ldots, x_n\}$ is a differential ideal. The question now is if there are a finite set of generators of $\mathcal{J}$, i.e., $\mathcal{J} = [q_1, \ldots, q_t]$ for some $q_i \in k\{x_r, \ldots, x_n\}$? This is an elimination problem, since $\mathcal{J}$ corresponds to all equations in the variables $x_r, \ldots, x_n$ and their derivatives which can be derived from the original set of equations.

Now consider a nonlinear state space description, where the nonlinearities are polynomial:

$$\Sigma = [\, \dot{x}_1 - f_1(\bar{x}, u), \ldots, \dot{x}_n - f_n(\bar{x}, u), y - h(\bar{x}) \,] \subseteq k\{x_1, \ldots, x_n, y, u\}.$$

The set of all input-output equations corresponds to the differential ideal

$$\Sigma^c = \Sigma \cap k\{y, u\}.$$

This differential ideal, called the input-output ideal of Σ, is studied in [42]. It is shown that despite the fact that Σ is finitely generated by construction, this may not be the case for Σ^c. It is also shown how this problem of a finite representation of a systems input-output equations can be resolved.

A related question is if there is a linear input-output relation although the state space description is nonlinear. This problem is investigated in [43].

The theory of input output relations can also be extended to systems with delays, see [41].

Quantifier Elimination

Many problems in control theory can be formulated as formulas involving polynomial equations, inequalities, quantifiers $(\exists, \forall)$ and logical connectivities $(\vee, \wedge)$. One example of such a formula is

$$\exists\, u \, \left[f(x, u) = 0 \ \wedge \ u^2 \leq 1 \right].$$

This can be seen as a description of all points, $x \in \mathbb{R}^n$ of a nonlinear system, $\dot{x} = f(x, u)$ which can be made stationary by use of some admissible control, $u \leq 1$.

The problem of *Quantifier Elimination*, (QE) consists of finding a formula without quantifiers (without u in the above case) which is equivalent to the original formula. This is always possible according to a result in the late forties by A. Tarski. However the calculations involved in this original

algorithm were to complex to be of any practical value. Lately there has been an increasing interest in QE due to the rapid development of computer algebra. The main part of implemented QE-algorithms consists of a method to compute a *Cylindrical Algebraic Decomposition*, (CAD) of $\mathbb{R}^n$ discovered 1973 by G. Collins. The method constructs a decomposition of $\mathbb{R}^n$ such that a given set of polynomials have constant sign on each component. Given such a CAD it is easy to determine if a system of polynomial equations and inequalities has a solution.

The CAD is represented by a number of sample points, one in each component and polynomials defining the boundaries of the components of the decomposition. Consider the real zero sets of the polynomials

$$F = \left\{ (x_1 - 2)^2 + (x_2 - 2)^2 - 1,\ (x_1 - 3)^2 + (x_2 - 2)^2 - 1 \right\}.$$

The corresponding CAD is shown in Figure 6.2 and consists of the distinct black "dots", "arcs" and "patches of white space".

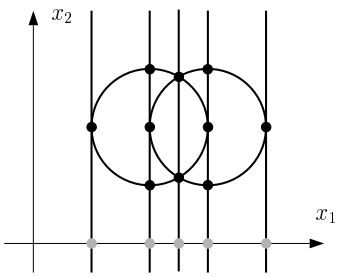


Figure 6.2: A Cylindrical Algebraic Decomposition of $\mathbb{R}^2$, w.r.t. F.

Possible applications of QE to control theory are e.g. problems regarding stationarity, stability and tracking.

A somewhat related problem is treated in [44]. Here the problem of eliminating latent variables in hybrid systems is considered. It is shown that comprehensive Gröbner bases play a natural role.

6.5 Robustness and Gain Scheduling using μ-methods

Stability and robustness analysis of linear systems are often handled using quadratic Lyapunov functions (LQG and H_∞). Related to this is the concept

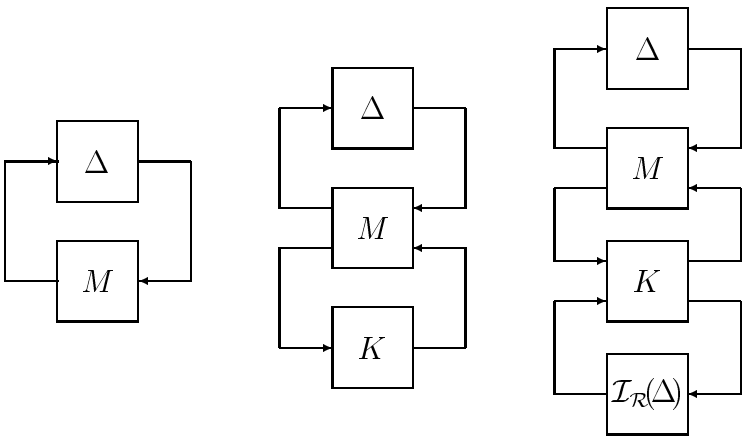


Figure 6.3: System with uncertainties. (a) The Δ block has a diagonal block structure, where each block may have different characteristics. (b) An uncertainty system with a controller K. (c) An uncertainty system with a gain scheduling controller. Here $\mathcal{I}_{\mathcal{R}}(\Delta)$ denotes a copy of some the uncertainties.

of structured singular values, or μ, which can be seen as an extension to H_∞ methods. These methods have attracted considerable interest since their introduction in 1982. The μ analysis can be seen as a refinement of the small gain theorem.

Robustness analysis with μ is often performed via a frequency sweep. One potential problem is then to know if the frequency grid is dense enough to assure stability. One way to avoid this problem is by covering a complete interval instead of discrete points only [96].

We can include knowledge about the structure of the uncertainties, which in general are linear or nonlinear operators. They are classified as (real) parametric if they are static and (complex) dynamic if they depend on previous values of its input.

Another characteristic of linear uncertainties is their time-varying properties. They can either be constant (time-invariant) or time-varying. Time-varying uncertainties can in turn be classified into two categories depending on whether the rate of variation is bounded or not. One method for analyzing systems with time-varying uncertainties with bounded rates of variation is by using uncertainty augmentation [121, 110].

The system is modeled as a system with feedback loops containing the parameter variations, uncertainties and perturbations, see Figure 6.3 (a). Using this formalism we are able to capture a quite general class of models. For

instance nonlinear systems can in some cases be modeled as linear systems with nonlinear "uncertainty" elements in the feedback path. Also, performance bounds can be included similarly. Linear matrix inequalities (LMIs) can also be used to formulate an upper bound of the robustness measure.

The synthesis problem is depicted in Figure 6.3 (b). Here the objective is to find a controller K in order to tolerate as large uncertainties as possible without making the closed loop system unstable. One approach to this problem is by the so called D-K iterations. In [95] we present a design method based on passivity argument when also parametric uncertainties are present.

The synthesis problem can be generalized to include gain scheduling by letting the controller have access to some of the uncertainties, denoted by $\mathcal{I}_{\mathcal{R}}(\Delta)$ in Figure 6.3 (c). Previous synthesis results involving (complex) dynamic uncertainties have recently been extended to also include (real) parametric uncertainties [98, 110].

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 [56, 97] that improves the approximation error compared to Hankel norm model reduction.

Chapter 7

Modelling

7.1 Physical modelling

The reason why the term *physical modelling* has been coined, is the need to distinguish between two extreme approaches to physical systems modelling. On the one extreme we have so called 'black-box modelling' in which case we only use measurements to fit an appropriate mathematical behavior model. On the other extreme we have physical modelling in which case we only use insight into the system structure combined with known physical laws to derive an appropriate mathematical model.

In practice though, none of the two extreme approaches are particularly fruitful in isolation. In order to model any non-trivial system, the two approaches will have to be combined. However, depending on the character of the system, one of the two modelling activities, *i.e.* physical modelling or parameter estimation, may dominate the overall modelling effort. In this section we focus on the physical modelling process.

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 and their interactions. The system is typically 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.

The second phase consists of *mathematical characterization* in which case the mathematical relations characterizing the physical mechanisms are specified. These relations are typically referred to as *constitutive relations*. By proper definition of the physical mechanisms used in the first phase, this step can partly be automated. This second phase constitutes a second step of abstraction away from the actual system.

In the third phase we *compile* the above relations into a suitable computational form, which can then be used for model analysis by any preferred numerical method.

The bond graph formalism provides significant support in all three of these phases. In the system reticulation phase, bond graphs significantly support the modelling task by providing a small and well defined set of primitive physical mechanisms. These elements are derived from first principles of energy conservation and help the modeller to make explicit as to which are the potentially relevant aspects of the observed system. Since they are based on energy concepts, they also correspond closely to primitive engineering concepts within several physical domains and applications.

The primitive bond graph elements have a well defined physical and mathematical semantics. Therefore the second phase is often trivial, and can in many cases even be automated. Finally, the derivation of *e.g.* differential and algebraic systems of equations (DAE systems) from a characterized bond graph, is completely straightforward.

One of the features of bond graphs is that they allow the modeller to *explicitly* represent the conceptual engineering knowledge that was used in the development of the mathematical model. This knowledge is otherwise 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, hydraulic valves, hydraulic 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.

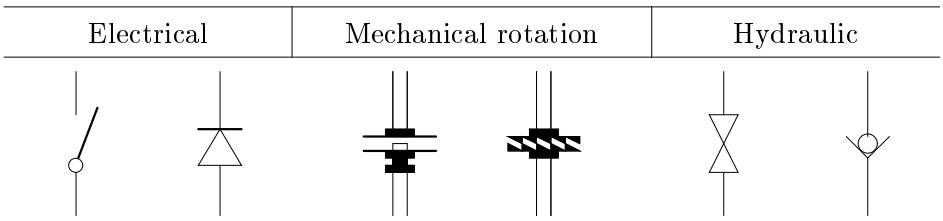


Figure 7.1: Some explicit discrete devices.

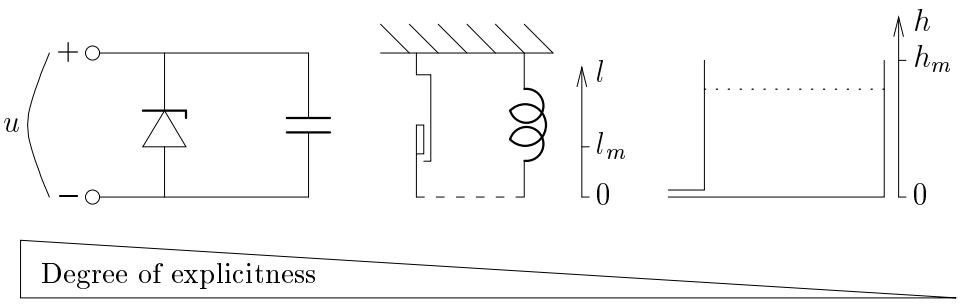


Figure 7.2: A spectrum of mode switching phenomena.

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.

Peculiar 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* [65].

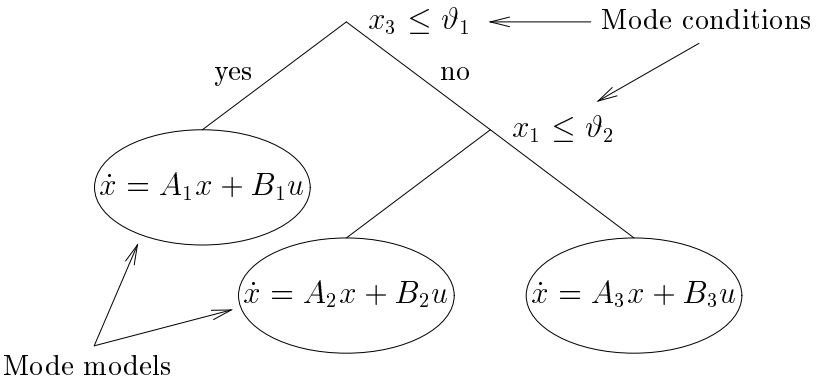


Figure 7.3: A model tree as a mode invariant representation.

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 1993 we 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 *effort* ($\mathcal{E}$) and *flow* ($\mathcal{F}$) state. In state $\mathcal{E}$ it acts as an ideal effort source with zero output and in state $\mathcal{F}$ it acts as a flow source, also with zero output. Note that the zero-valued sources have a particular *qualitative* meaning as particular boundary conditions. We have chosen the mnemonic **Sw** to represent the switch, noticing the close relation with the ideal sources. An immediate and interesting consequence of this definition is that the element will affect the overall causal structure of the model as the state of the switch changes.

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

7.5 An Example Hybrid System

Consider the hybrid system in Figure 7.4 (left). We are interested in studying the touch-down-process of this light aircraft, and therefore reticulate the system as depicted in the schematic diagram in Figure 7.4 (right). Here the damper r_1 and the spring k_1 represents the wheel itself

Applying the systematic method of mapping mechanical schematic diagrams to bond graphs, we immediately end up in the switched bond graph as depicted in Figure 7.5 (left). Note that the mapping procedure for standard bond graphs can be applied on switched bond graphs without any modification.

Generating the four potential causal bond graphs, *i.e.* the four computational structures, is now completely straightforward, using standard causality propagation rules. The overall mode structure of the system now becomes a four-state transition system and can be obtained from the two control structures in Figure 7.5 (right) by applying standard transition system composition [65]. We now have a complete computational model of the touch-down-process.

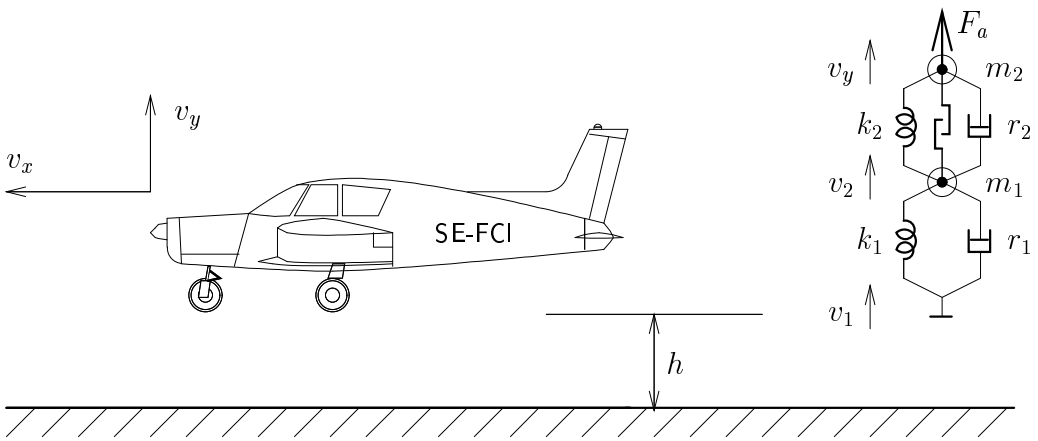


Figure 7.4: A hybrid system (left) and a reticulation of the same (right). m_1 is the mass of the wheel and damper sub-system and m_2 is the mass of the mainframe. F_a is the aerodynamic force acting on the mainframe.

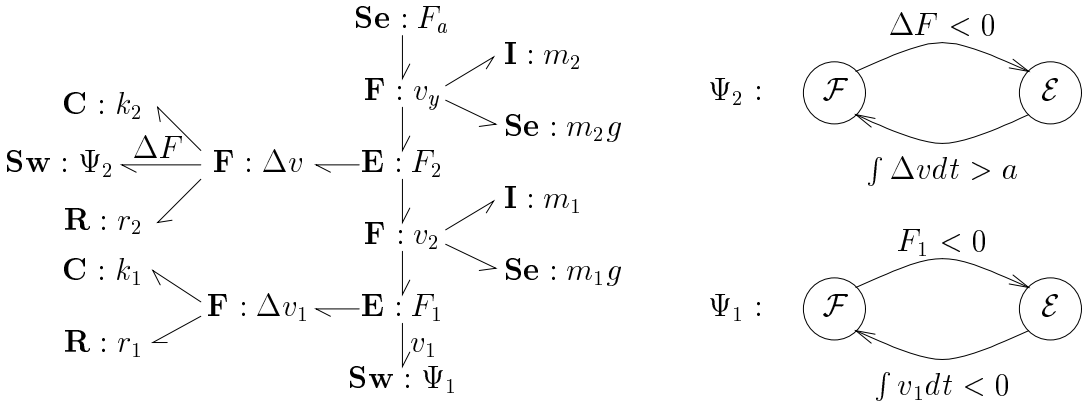


Figure 7.5: The acausal switched bond graph (left) and the control structures (right) of the landing aircraft system.

7.6 Composing Switched Bond Graphs

Composing switched bond graphs to a computational mathematical model in terms of a *hybrid mode transition system* is often straightforward. However, there are practical cases in which the composition no longer is trivial. This is the case when there are modes with no physical interpretation. Much of the current research effort is currently focused on methods to handle these cases so that the modularity and compositionality of classical bond graphs are maintained [119, 127, 128, 1, 64].

7.7 Verification of Hybrid Systems

One of the interesting uses of switched bond graphs, is to provide a front-end for hardware engineers to methods for formal verification of embedded real-time systems. In [138, 66] we report on the combination of switched bond graphs and *extended duration calculus* to model and analyze the JAS-39 Gripen hydromechanical landing gear subsystem [155]. This analysis involves a detailed model of the physical hardware, including electrical, hydraulic and mechanic components, as well as a model of the controlling software. The analysis concerns both static properties, such as 'the gear will never collide with the protecting doors' and dynamic properties such as 'under certain operating conditions, the gear will be fully extended and locked within T seconds after the pilot command has been issued'.

Chapter 8

Discrete Event Dynamic Systems

8.1 Introduction

In this chapter we will present work on dynamic systems with values in finite discrete domains. The underlying timing model may be asynchronous or synchronous.

One of the most challenging problems when developing a usable system theory for this class of systems is to deal with computational complexity. The worst case complexity of many analysis and design questions turn out to be NP–complete. We have pursued two completely different solutions to this dilemma: two different ways of representing and manipulating system dynamics (polynomials over finite fields and action structures).

Below we will present some of the capabilities of each of these representations and at the end we will see an industrial scale case study.

An input discrete event dynamic system is essentially a system of the form:

$$r(x(k), u(k), x(k+1)) \tag{8.1}$$

where $r \subseteq X \times U \times X$ is a relation that describes how subsequent states $x(k) \in X$ and $x(k+1) \in X$ are related through the input $u(k) \in U$. One common form for this relation is of course:

$$x(k+1) = f(x(k), u(k))$$

where $f : X \times U \to X$ is a function. In order to manipulate the system dynamics, e.g. analysis or design, we will essentially have to manipulate the relation r above. If the finite sets X and U are small this is no problem, but as many simple industrial examples indicate they are usually quite big, e.g. the

landing gear controller at the end has $|X| = 2^{26}$ and $|U| = 2^{37}$. These large state and input spaces are a result of concatenating several dynamical systems both horizontally and vertically and then deriving the global dynamics.

We have mainly worked with two types of representations: *action structures* and *polynomials over finite fields*.

Action Structures

Simplified action structures is a 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.

Polynomials

A polynomial model is essentially a set of polynomial equations of the form:

$$p_1(x, u, x^+) = 0, \ldots, p_k(x, u, x^+) = 0$$

where p_i are polynomials in the state x, input u and next state x^+. Any finite relation can be represented in this way and the case where the underlying field is $\{0, 1\}$ results in the well known Boolean polynomials. In order to analyze the system dynamics one essentially have to manipulate such systems of equations.

8.2 Simplified Action Structures (SAS)

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 the structure of the transition graph for each state variable. A more thorough description can be found in [68, 111]. The paper presents a planning algorithm that can deal with a restricted class of planning problems. The complexity of the algorithm increases polynomially with the number of actions and state variables. For example, we have modeled a simplified assembly line building Lego cars which fits into this restricted class.

8.3 Polynomial Dynamical Systems over Finite Fields

8.3.1 Polynomials over Finite Fields

Multivariate polynomials over finite fields are used to describe finite relations and functions. This is functionally complete description, i.e. all finite relations and finite functions can be described by polynomials over finite fields. We can also manipulate these finite relations (and functions) by performing polynomial operations on their polynomial representation. All the basic set operations are available, i.e. union, intersection, complement, projection and embedding. Additionally we map these relations through polynomial functions and obtain new polynomially represented relations. Finally we can also do these manipulations fairly efficiently through a recursive reduced representation analogous to the binary decision diagrams used for Boolean relations.

8.3.2 Modeling

It is fairly complicated to use these polynomials directly as a modeling tool, see e.g. [38, 60, 7]. A better approach is usually to use some form of model description language and then write a translator from that language into polynomials relations. This has been demonstrated for a number of different modeling formalisms and in particular the industrial case study below demonstrates a larger such exercise [112, 7, 134, 6].

8.3.3 Analysis

In many cases analysis of DEDS systems means computing the set of reachable states, since that set provide much of the global dynamics of the system. Reachability problems for discrete systems essentially corresponds to the stability problems for continuous systems.

Apart from reachability computations one is interested in if a DEDS system satisfy its specification. One convenient way of giving a specification is in terms of a temporal logic. We have extended the CTL temporal logic to polynomials over finite fields [39] and applied it to an industrial scale example [112] below.

8.3.4 Design

One of the primary goals for a systems theory for DEDS systems is of course in order to be able to do control design in a manner very much as is done for linear systems, say. Furthermore we would like to handle the size of systems that come up in industrial settings.

One classical design framework is the one suggested by Ramadge and Wonham in the mid eighties. The original papers did not have any large examples or suggest any computational techniques for dealing with large systems[1]. We can readily use our efficient polynomial methods to carry out this design [134].

Another design framework, has been studied in [38]. This approach is close in spirit to an optimization approach. The basic idea is to order the states in the plant state space according to an a criterion function and then use algebraic techniques to to derive a controller that is as greedy as possible in each step. In particular this technique will pinpoint states where several equally good control values exist, or where no control value exist.

8.4 A Case Study: The JAS Landing Gear Controller

Introduction

To explore the usefulness of symbolic and algebraic methods, we use polynomials over finite fields (see section 8.3.1) applied to DEDS with industrial sized complexity: The landing gear controller (LGC) of the Swedish fighter aircraft JAS 39 Gripen. (See Figure 8.1.)

[1]Except in the case when we essentially have a product independent plants and specifications.

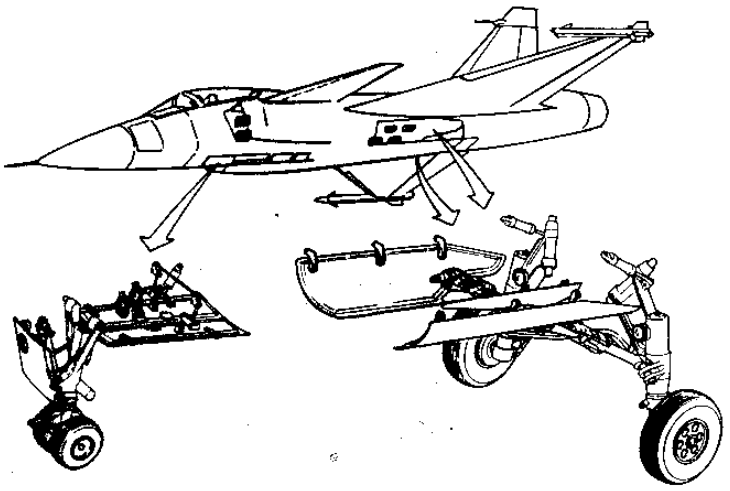


Figure 8.1: The landing gear system of the JAS 39 fighter aircraft.

The purpose of the LGC is to perform maneuvers of the landing gears and the corresponding doors which enclose the gears in retracted position. The controller is a software process that interacts with 5 binary actuators, 30 binary landing gear sensors, 2 binary pilot signals, and 5 integer mode signals from other subsystems in the aircraft. (See Figure 8.2.) The only formal description of the controller is a 1200 line Pascal code.

This section gives an overview of the project of doing static and dynamic analysis on the behavior of the LGC. This was made possible by modeling the LGC by a polynomial, i.e. compiling the Pascal implementation of the LGC to a polynomial relation. For a complete description of this project see [7, 6, 112].

Tools

The basic tools are based on a computationally efficient version of the underlying polynomial algorithms. Parts of this has been described in earlier versions of this yearly report and is available as reports and the remainder will be described in next years annual report.

The actual implementation of these ideas has been done in *Mathematica* and C. Essentially we have a polynomial manipulation package built in C which is linked into Mathematica trough the MathLink structured communication protocol. This means that we could write all the analysis and modeling (i.e. the compiler) parts of the software directly in Mathematica. This has

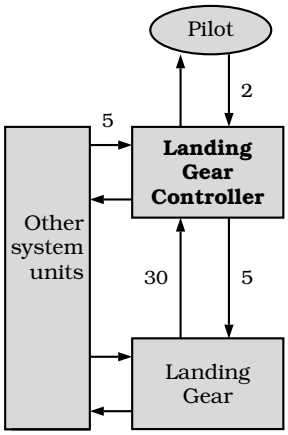


Figure 8.2: Controller interaction.

proved to be an efficient and highly extensible environment in which to carry out research into discrete systems.

For the LGC we used a *Binary Decision Diagrams* (BDD) implementation in C, i.e. polynomials over the binary field. All variables in the LGC system are represented binary and which makes it possible to use a normal form for boolean relations. See Figure 8.3.

Modeling

Here we will focus on the modeling of the landing gear controller which corresponds to the upper part of figure 8.4.

As mentioned in the introduction we build a polynomial model from the Pascal code. The polynomial model is denoted $M(z, z^+)$, where z and z^+ are the system variables[2] for present and next time instant respectively.

The Pascal code, representing the LGC, is executed once every sample, and the code represents a state space form of the LGC. Thus we need to analyze the code to determine what variables are inputs and outputs of the entire program. Variables that are both output and input variables have to be state variables. Other topics in the global analysis of the code are temporary variables and timers. The maximum range of the integer variables is determined to $0, 1, \ldots, 15$ which makes it possible to represent each integer variable by four Boolean variables.

[2]Input, state and output variables.

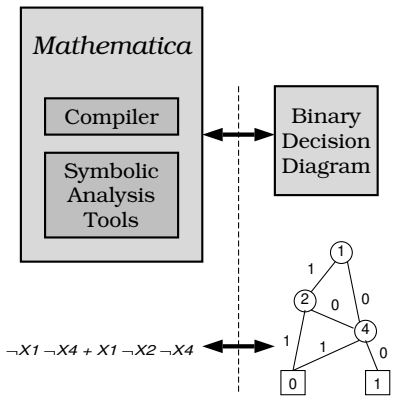


Figure 8.3: The symbolic tools used for the LGC.

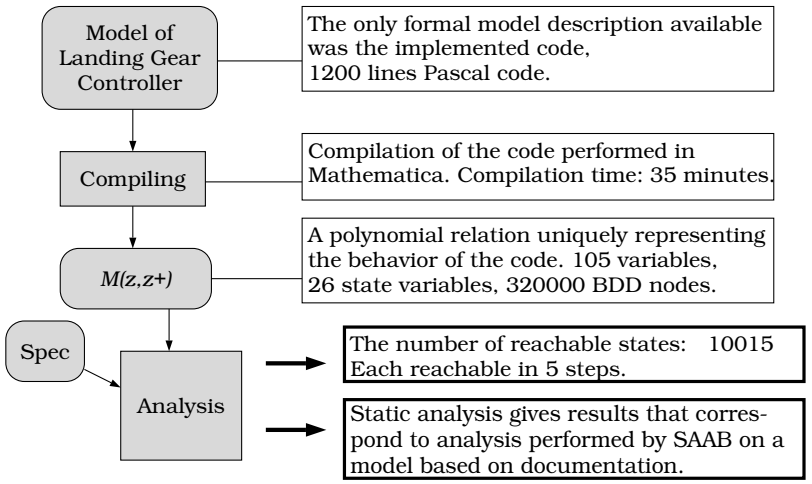


Figure 8.4: The modeling and analysis work performed on the LGC.

The translation from Pascal to Boolean expressions[3] follows the control flow graph of the program. The value of each program expression is determined by the current values of symbols and the actual program expression, i.e. the compilation function is of the form:

$$\Phi : Pascal \times State \to State$$

We store the current state of the program as a symbol table of the form:

$$\sigma = \{v_1 \mapsto e_1, \ldots, v_n \mapsto e_n\}$$

where each v_i is a variable or symbol and each e_i is a Boolean expression of input variables or the symbol $\perp$ indicating undefined values. The symbol table σ is initiated by variables that acts as place holders for the input, and by $\perp$ for the output variables. The symbol table is then updated by traversing the control flow graph of the Pascal code.

Suppose we have the Pascal expression

$$pe = \left(\begin{array}{l} \texttt{IF q THEN} \\ \quad \texttt{y1 := c} \\ \texttt{ELSE} \\ \quad \texttt{BEGIN} \\ \quad\quad \texttt{y1 := d;} \\ \quad\quad \texttt{y2 := e} \\ \quad \texttt{END;} \end{array} \right)$$

with the initial symbol table

$$\sigma = \{q \mapsto q^*, c \mapsto c^*, d \mapsto d^*, e \mapsto e^*, \\ y1 \mapsto y1^*, y2 \mapsto y2^*\}$$

we will get

$$\sigma^+ = \Phi(pe)\sigma = \{q \mapsto q^*, c \mapsto c^*, d \mapsto d^*, \\ e \mapsto e^*, y1 \mapsto (q^* \wedge c^*) \vee (\neg q^* \wedge d^*), \\ y2 \mapsto (q^* \wedge y2^*) \vee (\neg q^* \wedge e^*)$$

The final Boolean relation is computed from the final symbol table

$$\sigma_{final} = \{x^+ \mapsto f(x,u), y \mapsto g(x,u)\}$$
$$M(z, z^+) = x^+ \leftrightarrow f(x,u) \wedge y \leftrightarrow g(x,u)$$

where $z = [x, y, u]$.

The resulting relation for the LGC has 26 state variables and the relation $M(z, z^+)$ has 105 variables altogether. The size of the relation is approximately 320 000 nodes as a BDD and takes approximately 35 minutes to compute on a regular workstation.

[3]Boolean expressions are essentially polynomials over the field $\mathbf{F}_2$.

Analysis

Here we will focus on the modeling of the landing gear controller which corresponds to the lower part of figure 8.4.

We use the relation $M(z, z^+)$ to analyze the LGC behavior in a number of ways. First we compute the set of reachable states in the LGC. This set is represented algebraically by a relation $R(x)$. The number of reachable states turns out to be 10 015 which is far below the possible number which is $2^{26} \approx 10^8$. We can restrict the original relation as

$$\hat{M}(z, z^+) = R(x) \wedge M(z, z^+) \wedge R(x^+)$$

which gives a significantly simpler relation.

The static analysis of $\hat{M}(z, z^+)$ is performed by adding constraints $P(u)$ to the inputs of the LGC, and then analyze what effect this gives to the outputs.

Results on dynamic closed loop analysis is not available yet. However we use the same tools as to compute the set of reachable states. The specifications of the behavior are represented by temporal logic expressions, used together with the model to compute e.g. the set behaviors that might reach a forbidden state in the future.

8.5 Conclusion

We have described some aspects of a theory for discrete event dynamic systems. In particular we have covered: *modeling*, *analysis* and *design*. We have also seen that this can be scaled up to industrial size examples. In order to reach the industrial size examples we have found that tool and algorithm development become quite crucial. In fact for discrete systems one can almost claim that there is no useful theory without an algorithmic component. This will continue to be our guiding principle in the development of a theory for discrete (event) dynamic systems.

Appendix A

Personnel

Lennart Ljung is professor and head of the control group since 1976. He was born in 1946 and received his Ph.D. in Automatic Control from Lund Institute of Technology in 1974. He is a member of the Royal Swedish Academy of Engineering Sciences (IVA) and the Royal Swedish Academy of Sciences (KVA), and an IFAC Advisor. He is also an IEEE Fellow and associate editor of several journals.
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Jonas Plantin was born in 1966. He received his M.Sc. in Applied Physics and Electrical Engineering and his Tekn.lic in 1995 both from Linköping University in 1992. His current research interest is in the field of discrete event systems. He is currently employed by Ericsson Radio Systems AB in Stockholm
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Johan Gunnarsson was born in 1967. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1992 and his Tekn.lic. in 1995 both at Linköping University. His current research interest is in the field of discrete event systems.
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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.
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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.
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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.
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Anders Stenman was born in Gävle, Sweden in 1966. He received his M.Sc. in Computer Science and Engineering from Linköping University in 1993. His current research interests include "just in time"-models and the use of database systems in system identification.
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Jan Palmqvist was born in 1961. He received his M.Sc. in Applied Physics and Electrical Engineering in 1986 at Linköping University. He has been with Saab Military Aircraft since 1989 and in 1994 he also joined the Control Group as part time PhD student. His current research interest is in the field of signal processing.
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Magnus Andersson was born in 1968. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1994 from Linköping University. His current research is in the field of system identification.
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Magnus Larsson was born in 1970. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1995 at Linköping University. His current research interest is in the field of discrete event systems and diagnosis.
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Magnus 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.
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Ulla Salaneck and Ingegerd Stenlund secretaries for the control group. Ingegerd Stenlund left the Control Division in January 1995, after working there for exactly twenty years.
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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 spent 1 year as a postdoc in Linköping during 1994-95. His research interests include control-oriented system identification, adaptive/predictive control, and signal processing. He is now employed by Treiberg Controls Inc. in Toronto, Canada.
email: niu@ecf.toronto.edu

Ashok Tikku was born in 1968, he got his Ph.D. from University of California at Berkeley in 1994 and spent one year as a postdoc in Linköping.

Chun Tung Chow was born in 1967 and received his Ph.D. from Cambridge University and spent 6 months in Linköping as a postdoc during 1995.

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: Torkel Glad.

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

D Computer Engineering Program. 120 participants. Lecturer: Fredrik Gustavsson.

Im Industrial Engineering and Management, Mechanical variant. 80 participants. Lecturer: Håkan Hjalmarsson.

Ie Industrial Engineering and Management, Electrical variant. 60 participants. Lecturer: Jonas Sjöberg.

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: Fredrik Gustavsson.

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

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

B.Sc. (tekn.kand.) - program

- *Automatic control, EI* (Electrical Engineering) 5 units, 60 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, 60 participants. Contents: Sequential control and logic controllers. A typical industrial control system. Lecturer: Kent Hartman.

- *Automatic control, MI* (Mechanical Engineering) 4 units, 35 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

- *Optimal Control.* Lecturer: Torkel Glad. Literature: G. Leitman, The calculus of variations and optimal control, Plenum Press 1981.
- *Robust multivariable control.* Lecturer: Lennart Ljung. Literature: J. M. Maciejowski, Multivariable feedback design, Addison-Wesley, 1989.
- *Linear systems.* Lecturer: Torkel Glad. Literature: T. Kailath, Linear systems, Prentice Hall, 1980.
- *History of control.* A series of seminars by the participants.

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 6 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
- 2 Sun SPARCserver 10 (2*2 hyperSPARC)
- 1 Sun SPARCsystem 300 server
- 12 Sun SPARCstation 20
- 5 Sun SPARCstation 10
- 16 Sun SPARCstation 5
- 5 Sun SPARCstation LX
- 5 Sun SPARCstation 2

- 2 AST Bravo LC 4/66d
- 1 HP LaserJet 4 Si/MX Postscript laser printer
- 1 HP ColorJet Postscript laser printer
- 2 HP LaserJet 5 MPPostscript laser printer

The Sun workstations run Solaris 2.5 and CDE (Common Desktop Environment). OpenWindows 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, MATRIXx, 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

Nonsmooth feedback stabilization of nonlinear systems **Professor S. Celikovsky**, Prague, September 14, 1994.

L1 optimization **Professor A. Barabanov,** St Petersburg State University, September 15, 1994.

Models of disturbances **Professor A, Barabanov,** St Petersburg State University, September 15, 1994.

History of the Mechanical and Electronic Differential analyzers **Professor H. Paynter**, MIT, October 6, 1994.

Statics and Dynamics of Chemical Networks **Professor H. Paynter**, MIT, October 6, 1994.

Real time modelling and control of physical experiments **Professor H. Paynter**, MIT, October 7, 1994.

Efficient COCOLOG logic control: Markovian fragments and 2 hierarchies **Dr Yuanjun Wei**, McGill University, Montreal, October 20, 1994.

Overview of the Parsytec GC-PowerPlus, hardware and software **Doc. P. Fritzson** IDA, Linköping University, January 26, 1995.

Petri nets and modeling of systems **Zebo Peng**, Dept, of Computer and Information science, Linköping University, February 16, 1995.

Modeling a simulation of hybrid systems in OmSim **Dr Mats Andersson**, Lund Institute of Technology, February 23, 1995.

Neural network modeling for simulation with neural networks **Isabelle Rivals**, University of Paris, March 6, 1995.

Controllability and observability in a new perspective **Professor J.C. Willems**, University of Groningen, Groningen, The Netherlands, March 21, 1995.

Adaptive control of periodic and chaotic nonlinear oscillations **Professor A. Fradkov**, Academy of Sciences of Russia, St. Petersburg, March 30, 1995.

Non-convex optimal control problems **Professor V. Yakubovich**, St Petersburg University, St Petersburg, March 30, 1995.

The current status in the area of control of mobile telephone networks **Bo Kvarström**, Ericsson Radio, Linköping, April 6, 1995.

Prediction Control of Crude Distillation Unit at Nynäs Refinery in Nynäshamn **T. Montin** Nynäs AB, Nynäshamn, Sweden, April 20, 1995.

On Recursive Nonlinear estimation **Dr. R. Kulhavy**, Inst. of Information Theory and Automation, Prague, Checkia, May 3, 1995

Frequency domain identification: a mature alternative? **Rik Pintelon**, Vrije Universiteit Brussel, Brussels, Belgium, May 4, 1995.

An Identification Approach to Autotune Control **Professor K. Godfrey**, University of Warwick, England, May 4, 1995.

Knowledge-Based Neural Modeling, an Application to Fault Detection in an Industrial Distillation Column **Professor G. Dreyfus**, ESPCI, Paris, France, May 12, 1995.

Application of Flatness, Quasi-Static State Feedback Linearization and Nonlinear Observers, **Dr. J. Rudolph**, Universität Stuttgart, Stuttgart, Germany, May 17, 1995.

On Repetitive Control **Dr. G. Hillerström**, Luleå Institute of Technology, Luleå, Sweden, May 18, 1995.

Appendix E

Travel and Conferences

Lennart Ljung participated in the IFAC Symposium on System Identification in Copenhagen, Denmark, July 4-7, and in the Gordon Conference on Statistical Methods in Chemistry, Hampton, NH, August 1-5. He then took part in SIMS'94 in Stockholm, August 17-19, and in the NATO Advanced Summer Institute "From Identification to Learning" in Como, Italy, August 29 to September 2. He visited Kassel Institute of Technology Spetember 6 –8 and was at the European Research Network on System Identification, (ERNSI meeting) in Holland, September 21 to 23. He then participated in Reglermötet-94 at Västerås, October 24-26 and in the IEEE Conference on Decision and Control in Lake Buena Vista, Florida, USA, December 12-16. January 20 has was in a thesis jury at ESPCI, Paris and on February 24 in another thesis jury at Leuven, Belgium.

He visited the Wright-Patterson Airforce base in Dayton, Ohio, April 1 - 4, and Dartmouth College, NH, April 5-6. He was at the ERNSI meeting in Padova, Italy, June 7-9, at the Dutch Control Network's symposium in Groningen, June 14-16, and participated in the International Conference on Communications, Computing, Control and Signal Processing – to honor the contributions of Professor Thomas Kailath –, at Stanford, June 22–26, 1995.

Torkel Glad participated in the SIMS'94 conference in Stockholm August 17–19 1994 and in the Reglermöte in Västerås during October 25–26 1994.

Anders Ericsson participated in the third and fourth European Research Network on System Identification, ERNSI workshops in Noordwijkerhout, the Netherlands, September 21 to 23 and in Padova, Italy, June 7 to 9.

Svante Gunnarsson participated in the 10th IFAC Symposium on System Identification, Copenhagen, Denmark, July 4-6, 1994. He also took part in the 3rd ERNSI Workshop in System Identification, Noordwijkerhout, The Netherlands, September 21-23, 1994 and the 4th ERNSI Workshop in System Identification, Padova, Italy, June 7-9. He attended the IEEE Conference on Decision and Control, Orlando, Florida, USA, December 14-1

Kent Hartman participated in the "Reglermöte 94" in Västerås, Sweden, October 1994 and "Ingenjörsforum's" "Industrial need in Education" in Borås, Sweden June 1995.

Anders Helmersson participated in the '94 American Control Conference in Baltimore, Maryland, June 28 - July 1. He took part in the Swedish control conference in Västerås, Sweden in October 25-26. He then participated in the '94 IEEE conference on Decision and Control in Orlando, Florida in December 14-16.

Håkan Hjalmarsson participated in the IEEE 33rd Conference on Decision and Control in Lake Buena Vista, Florida, USA, December 14-16.

Inger Klein attended the "Reglermöte 94" in Västerås, Sweden, October 1994. In June she attended "Robotikdagarna 1995" in Linköping, Sweden.

Tomas McKelvey participated in the 10th IFAC Symposium on System Identification, Copenhagen, Denmark, July 4-6. September 21-23 he took part in the 3rd ERNSI Workshop on System Identification, Noordwijkerhout, The Netherlands. He participated in NFFP project meeting on Model Updating, Jönköping, Sweden, October 30. He visited Reglermöte'94, Västerås, Sweden, October 25-26. November 7-11 he visited ELEC at Vrije Universiteit, Brussels, Belgium and November 12-15 ESAT-SISTA at Katholieke Universiteit, Leuven, Belgium. December 14-16 he participated in the 33rd IEEE Conference on Decision and Control. He attended NFFP project meetings on Model Updating in Jönköping, January 10 and at Saab Military Aircraft, Linköping Sweden, May 10. June 7-9 he attended the 4th ERNSI Workshop on System Identification, Padova, Italy.

Peter Lindskog participated in the 10th IFAC Symposium on System Identification (SYSID'94) in Copenhagen, Denmark, July 4-7. He then attended the 3rd and 4th ERNSI Workshops on System Identification in Noordwijkerhout, the Netherlands, September 21 to 23 and in Padova, Italy, June 7-9.

Jonas Plantin participated in the 1995 American Control Conference in Seattle, June 1995.

Johan Gunnarsson participated in the 1995 American Control Conference in Seattle, June 1995.

Predrag Pucar participated in the 10th IFAC Symposium on System Identification SYSID '94, Copenhagen, Denmark, July 4-6. He then attended the Frame Program Conference in Telecommunication, organized by NUTEK in Uppsala, Sweden, August 28-29. September 21-23 he took part in the 3rd ERNSI Workshop in System Identification, Noordwijkerhout, The Netherlands. He then took part in the 1995 International Conference on Acoustics, Speech, and Signal Processing (ICASSP-95) in Detroit, Michigan, U.S.A., May 9-12. June 7-9 he attended the 4th ERNSI Workshop on System Identification located in Padova, Italy.

Jonas Sjöberg took part in the European Research Network on System Identification, ERNSI (meetings) in Noorvijkerhaut, The Netherlands, September, and in Padova, Italy, June. He participated in the national control conference "Reglermöte '94" in Västerås, November. In April he visited the Faculty of Agricultural Eng., Technion, Haifa and the Faculty of Engineering at Tel Aviv University, Israel.

Anders Stenman participated in the 4th ERNSI Workshop on System Identification in Padova, Italy, June 7-9.

Jan-Erik Strömberg attended the Second International Conference on Bond Graph Modeling and Simulation (ICBGM '95), Las Vegas, January 15–18.

Ingegerd Stenlund and *Ulla Salaneck* participated in "Sekreterarträffen" in Åbo, Finland in September 1994, in "Reglermöte'94" in Västerås and in "Sekreterarträffen" in New York in November 1994.

Appendix F

Lectures by the Staff

Håkan Fortell: *On Zeros of Regular Transfer Functions and the Zero Dynamics* , 33rd IEEE Conference on Decision and Control, December 16, Lake Buena Vista, Florida.

Håkan Fortell: *Calculation of Zero Dynamics using the Ritt Algorithm*, 33rd IEEE Conference on Decision and Control, December 16, Lake Buena Vista, Florida.

Håkan Fortell: *Calculation of Zero Dynamics for Affine MIMO-Systems using the Ritt Algorithm*, 3rd IFAC Symposium on Nonlinear Control Systems Design, July 26, Tahoe City, California.

Torkel Glad: *Applications of simulation in control.* Plenary lecture, The SIMS'94 conference, Augusti 19 1995.

Torkel Glad: *Application of modern control techniques to flight control*, FMV Prov, Linköping, October 28, 1994.

Torkel Glad: *Stabilizable regions for unstable systems with rate and amplitude bounds on the control*, NOLCOS'95, Tahoe City, Ca, USA, June 27 1995 (presented by Håkan Fortell)

Svante Gunnarsson: *On time-frequency resolution of signal properties using parametric techniques*, 33rd IEEE Conference on Decision and Control, Orlando, Florida, USA, December 15, 1994.

Anders Helmersson: *A Finite Frequency Method for μ-Analysis*, Swedish Control Conference, Västerås, Sweden, October 26, 1994.

Anders Helmersson: *Model Reduction using LMIs*, 33rd IEEE Conference on Decision and Control, Orlando, Florida, December 16, 1994.

Håkan Hjalmarsson: *A Convergent Iterative Restricted Complexity Control Design Scheme*, 33rd IEEE Conference on Decision and Control, December 15, Lake Buena Vista, Florida, USA.

Inger Klein: *Automatic Synthesis of Sequential Control Schemes*, Chalmers University of Technology, Gothenburg, Sweden, Februar 3, 1995.

Inger Klein: *Automatic Synthesis of Control Programs for an Assembly Line*, "Robotikdagarna 1995", Linköping, Sweden, June 7, 1995.

Peter Lindskog: *Semi-Physical Modeling Tools*, The 10th IFAC Symposium on System Identification, Copenhagen, Denmark, July 7, 1995.

Lennart Ljung: *Neural Networks in System Identification*, The IFAC Symposium on System Identification, Copenhagen, Denmark, July 6, 1994.

Lennart Ljung: *A Graphical User Interface to the System Identification Toolbox* , The IFAC Symposium on System Identification, Copenhagen, Denmark, July 6, 1994.

Lennart Ljung: *A Unifying view of Disturbances in Identification*, The IFAC Symposium on System Identification, Copenhagen, Denmark, July 7, 1994.

Lennart Ljung: *A Perspective on System Identification*, The Gordon Conference on Statistical Methods in Chemistry, Hampton, NH, August 3, 1994.

Lennart Ljung: *From Data To Model: A guided tour of System Identification*, Plenary Address, The SIMS-94 Conference, Stockholm, August 17, 1994.

Lennart Ljung: *Identifiability, Physical and semi-physical models in System Identification*, The NATO Advanced Summer Institute on "From Identification to Learning", Como, Italy, August 31, 1994

Lennart Ljung: *Neural Network Techniques from an identification perspective*, The NATO Advanced Summer Institute "From Identification to Learning", Como, Italy, Sept 1, 1994

Lennart Ljung: *A Survey of Modern Identification Theory*, 3 lectures at Fachgebiet Regelungstechnik, University of Kassel, Germany, Sept 6 and 7, 1994.

Lennart Ljung: *Everything you need to know about Neural Networks*, ERNSI Meeting in Holland, September 22, 1994.

Lennart Ljung: *Aspects on accelerated convergence in stochastic approximation schemes*, 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida, USA, December 16, 1994.

Lennart Ljung: *The role of model validation for assessing the size of the unmodelled dynamics*, 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida, USA, December 15, 1994.

Lennart Ljung: *From Data to Model: A Guided Tour*, The Wright-Patterson Airforce Base, Dayton, Ohio, APril 3, 1995.

Lennart Ljung: *From Data to Model: A Guided Tour*, Alphatech, Inc, Boston, MA, April 5, 1995.

Lennart Ljung: *An Overview of System Identification*, Dartmouth College, New Hampshire, April 6, 1995.

Lennart Ljung: *Non-linear Black Box models in System Identification* ERNSI meeting, Padova, Italy, June 7, 1995.

Lennart Ljung: *Non-linear Black Box models in System Identification* Dutch Control Network meeting, Groningen, Holland, June 15, 1995.

Lennart Ljung: *Non-linear Black Box models in System Identification* International Conference on Communications, Computing, Control and Signal Processing, in the Honor of Tom Kailath's 60:th Birthday, Stanford, June 24, 1995.

Tomas McKelvey: *Fully Parametrized State-Space Models in System Identification*, 10th IFAC Symposium on System Identification, Copenhagen, Denmark, July 5, 1994.

Tomas McKelvey: *Are Identifiable Parametrizations Necessary*, 3rd ERNSI Workshop on System Identification, Noordwijkerhout, The Netherlands, September 25, 1994.

Tomas McKelvey: *A Non-Iterative State-Space Identification Algorithm*, Reglermöte'94, Västerås, Sweden, October 25, 1994.

Tomas McKelvey: *Part I: A Subspace Based Identification Method in the Frequency Domain, Part II: Vibration Analysis of the SAAB 2000 Commuter Aircraft*, Vrije Universiteit, Brussels, Belgium, November 8, 1994.

Tomas McKelvey: *Part I: A Subspace Based Identification Method in the Frequency Domain, Part II: Vibration Analysis of the SAAB 2000 Commuter Aircraft*, Katholieke Universiteit, Leuven, Belgium, November 15, 1994.

Tomas McKelvey: *A combined state-space identification algorithm applied to data from a modal analysis experiment on a separation system*, 32nd IEEE Conference on Decision and Control, San Antonio, Texas, USA, December 15, 1994.

Tomas McKelvey: *An Efficient Frequency Domain State-Space Identification Algorithm* , 33nd IEEE Conference on Decision and Control, Lake Buena Vista, Florida, USA, December 16, 1994.

Tomas McKelvey: *An Efficient Frequency Domain State-Space Identification Algorithm: Robustness and Stochastic Analysis* , 33nd IEEE Conference on Decision and Control, Lake Buena Vista, Florida, USA, December 16, 1994.

Tomas McKelvey: *Model Reduction in a System Identification Context*, 4th ERNSI workshop on System Identification, Padova Italy, June 7, 1995.

Jonas Plantin: Automatic Synthesis for Simultaneous Supervision and Control – a First Example, ACC'95, Seattle, USA, June 1995.

Jonas Sjöberg: *System Identification Aspects on Neural Networks*, Faculty of Agricultural Eng., Technion, Haifa, Israel, April, 1995.

Jan-Erik Strömberg: *Switched Bond Graphs*, Dept. of Computer and Information Science, Linköping University, Linköping, December 12, 1994.

Jan-Erik Strömberg: *Switched Bond Graphs: Towards Systematic Composition of Computational Models*, the Second International Conference on Bond Graph Modeling and Simulation (ICBGM '95), Las Vegas, January 15, 1995.

Jan-Erik Strömberg: *Modelling Mode-Switching in Dynamic Systems*, Reglerteknik, Chalmers Tekniska Högskola, January 21, 1995.

Jan-Erik Strömberg: *Hybrid Modelling of the JAS-39 Gripen Landing Gear and Supply System*, First COHSY Workshop on Hybrid Systems Verification, Linköping University, Linköping, March 22, 1995.

Appendix G

Appendix G
Publications

Ph.D. Theses

[1] Jan-Erik Strömberg. *A Mode Switching Modelling Philosophy.* PhD thesis, Linköping University, Linköping, 1994. Dissertation no. 353.

[2] Ke Wang Chen. *Transformation and Symbolic Calculations in Filtering and Control.* PhD thesis, Linköping University, Linköping, 1994. Dissertation no. 361.

[3] T. McKelvey. *Identification of State-Space Models from Time and Frequency Data.* PhD thesis, Linköping University, Linköping, May 1995. Dissertation no. 380.

[4] Jonas Sjöberg. *Non-Linear System Identification with Neural Networks.* PhD thesis, Linköping University, Linköping, 1995. Dissertation no. 381.

Licentiate Theses

[5] P. Lindskog. *Algorithms and Tools for System Identification Using Prior Knowledge.* Licentiate thesis LIU-TEK-LIC-1994:42, Department of Electrical Engineering, Linköping University, Linköping, Sweden, September 1994.

[6] Jonas Plantin. Algebraic methods for verification and control of discrete event dynamic systems. Linköping studies in science and technology. Thesis no.501, LiU-Tek-Lic-1995:33, ISBN 91-7871-194-3, Department of Electrical Engineering, Linköping University, Sweden, June 1995.

[7] Johan Gunnarsson. On modelling of discrete event dynamic systems, using symbolic algebraic methods. Linköping studies in science and technology. Thesis no.502, LiU-Tek-Lic-1995:34, ISBN 91-7871-194-3, Department of Electrical Engineering, Linköping University, Sweden, June 1995.

Journal Papers

[8] T. Andersson and P. Pucar. Estimation of residence time in continuous flow systems with dynamics. *Journal of Process Control*, 5:9–17, February 1995.

[9] L. Gou and L. Ljung. Exponential stability of general tracking algorithms. *IEEE Trans. Automatic Control*, 40:1376–1387, August 1995.

[10] L. Gou and L. Ljung. Performance analysis of general tracking algorithms. *IEEE Trans. Automatic Control*, 40:1388–1402, August 1995.

[11] J. Sjöberg, Q. Zhang, L. Ljung, A. Benveniste, B. Delyon, P.-Y. Glorennec, H. Hjalmarsson, and A. Judisky. Nonlinear black-box modeling in system identification: a unified overview. *Automatica*, 31:1691–1724, December 1995.

[12] A. Juditsky, H. Hjalmarsson, A. Benveniste, B. Delyon, L. Ljung, J. Sjöberg, and Q. Zhang. Nonlinear black-box models in system identification: Mathematical foundations. *Automatica*, 31:1725–1750, December 1995.

[13] J. Sjöberg and L. Ljung. Overtraining regularization and searching for minimum with application to neural nets. *Int. J. Control*, 1995.

[14] T. McKelvey, H. Akçay, and L. Ljung. Identification of infinite dimensional systems from frequency response data. *Automatica*, 1995. Accepted for publication.

[15] L. Ljung. Building models from frequency domain data. In K.J. Åström, G.C.Goodwin, and P.R Kumar, editors, *Adaptive Control, Filtering and Signal Processing*, volume 74 of *The IMA volumes in Mathematics and its Applications*, pages 229–240. Springer-Verlag, New York, 1995.

[16] T. McKelvey and H. Akçay. Subspace based system identification with periodic excitation signals. *System & Control Letters*, 1995. Accepted for publication.

[17] F. Gustafsson and B. Wahlberg. Blind equalization by direct examination of the input sequences. *IEEE Tr. on Communications*, 43(7):2213–2222, 1995.

[18] F. Gustafsson and H. Hjalmarsson. 21 ML estimators for model selection. *Automatica 31:10*, 1995.

[19] H. Hjalmarsson and F. Gustafsson. Composite modeling of transfer functions. *IEEE Tr. on Automatic Control*, 40(5):820–832, 1995.

[20] F. Gustafsson. The marginalized likelihood ratio test for detecting abrupt changes. *To appear in IEEE Tr. on Automatic Control*, 41(1), 1996.

[21] L. Ljung, J. Sjöberg, and H. Hjalmarsson. On neural network model structures in system identification. In S. Bittanti, editor, *Proc. from the NATO Advanced Summer Institute "From Identification to Lear ning"*, pages 162–195. Springer Verlag, 1995.

[22] F. Gustafsson. Determining the initial states in forward-backward filtering. *To appear in IEEE Tr. on Signal Processing*, 1996.

Conference Papers

[23] T. Abrahamsson, T. McKelvey, and L. Ljung. A study of some approaches to vibration data analysis. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 3, pages 289–294, Copenhagen, Denmark, July 1994.

[24] H. Kaufman, S. Koch, and L. Ljung. The EKF, RPEM and recursive maximum likelihood method in a simple application to image restoration. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 3, pages 441–446, Copenhagen, Denmark, July 1994.

[25] L. Ljung. A graphical user interface (GUI) to the system identification toolbox. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 4, pages 29–33, Copenhagen, Denmark, July 1994.

[26] H. Hjalmarsson and L. Ljung. A unifying view of disturbances in identification. In *Proc. 10th IFAC symposium on System Identification (SYSID'94)*, volume 2, pages 73–78, Copenhagen, Denmark, July 1994.

[27] T. Andersson, P. Pucar, and L. Ljung. Identification aspects of intersample input behavior. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 3, pages 137–142, Copenhagen, Denmark, July 1994.

[28] T. McKelvey. Fully parametrized state-space models in system identification. In *Proceedings of the 10th IFAC Symposium on System Identification (SYSID'94)*, volume 2, pages 373–378, Copenhagen, Denmark, July 1994.

[29] P. Lindskog and L. Ljung. Tools for semi-physical modeling. In *Proceedings of the 10th IFAC symposium on Identification (SYSID'94)*, volume 3, pages 237–242, Copenhagen, Denmark, July 1994. Revised version accepted for publication in Int. J. Adapt. Control Signal Process.

[30] T. Andersson and P. Pucar. Estimation of residence time in continuous flow systems with dynamics. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 3, pages 401–406, Copenhagen, Denmark, July 1994.

[31] J. Sjöberg and L. Ljung. Criterion minimization using estimation data and validation data. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 1, pages 187–190, Copenhagen, Denmark, July 1994.

[32] J. Sjöberg, H. Hjalmarsson, and L. Ljung. Neural networks in system identification. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 2, pages 49–72, Copenhagen, Denmark, 1994. Available by anonymous ftp `130.236.24.1`.

[33] H. Akçay, H. Hjalmarsson, and L. Ljung. On the choice of norms i system identification. In *Proceedings 10th IFAC Symposium on System Identification (SYSID'94)*, volume 2, pages 103–108, Copenhagen, Denmark, 1994.

[34] H. Akçay and H. Hjalmarsson. The least-squares identification of fir systems subject to worst-case noise. In *Proceddings 10th IFAC Symposium on System Identification (SYSID'94)*, volume 2, pages 85–90, Copenhagen, Denmark, 1994.

[35] H. Hjalmarsson and L. Ljung. A unifying view of disturbances in identification. In *Proceedings 10th IFAC Symposium on System Identification (SYSID'94)*, volume 2, pages 73–78, Copenhagen, Denmark, 1994.

[36] U. Zhu, P. van Overschee, B. De Moor, and L. Ljung. Comparison of three classes of identification methods. In *Proc. 10th IFAC Symposium on System Identification (SYSID'94)*, volume 1, pages 1.175–1.180, Copenhagen, Denmark, 1994.

[37] S. Gunnarsson. "On covariance modification and regularization in recursive least squares identification",. In *Proceedings 10th IFAC Symposium on System Identification (SYSID'94)*, pages 661–666, Copenhagen, Denmark, 1994.

[38] Johan Gunnarsson and Jonas Plantin. Control law synthesis for a discrete event system. In *Reglermöte '94*, 1994.

[39] R. Germundsson. Verifying temporal properties in discrete event systems. In *Reglermöte '94*, 1994.

[40] T. McKelvey. A non-iterative state-space identification algorithm. In *Reglermöte '94*, 1994.

[41] K. Forsman and L. Habets. Input-output equations and observability for polynomial delay systems. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 880–882, 1994.

[42] K. Forsman and M. Jirstrand. Some finiteness issues in differential algebraic systems. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 1112–1117, 1994.

[43] K. Forsman. On nonlinear systems with linear dynamics. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 1778–1783, 1994.

[44] K. Forsman. Hybrid control systems and comprehensive Gröbner bases. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 4092–4097, 1994.

[45] H. Fortell. On zeros of regular transfer functions and the zero dynamics. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 3265–3270, 1994.

[46] H. Fortell. Calculation of zero dynamics using the Ritt algorithm. In *33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 3271–3276, 1994.

[47] T. McKelvey and H. Akçay. An efficient frequency domain state-space identification algorithm: Robustness and stochastic analysis. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 3348–3353, December 1994.

[48] T. McKelvey. A combined state-space identification algorithm applied to data from a modal analysis experiment on a separation system. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 2286–2287, December 1994.

[49] T. McKelvey and H. Akçay. An efficient frequency domain state-space identification algorithm. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 3359–3364, December 1994.

[50] L. Ljung. Aspects on accelerated convergence in stochastic approximation schemes. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 1649–1652, December 1994.

[51] F. Gustafsson, S. Gunnarsson, and L. Ljung. On time-frequency resolution of signal properties using parametric techniques. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 2259–2264, December 1994.

[52] L. Guo and L. Ljung. Performance analysis of general tracking algorithms. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 2851–2855, December 1994.

[53] L. Guo and L. Ljung. The role of model validation for assessing the size of the unmodeled dynamics. In *Proc. 33rd IEEE Conference on Decision and Control, Lake Buena Vista, Florida*, pages 3894–3899, December 1994.

[54] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. "A convergent iterative restricted complexity control design scheme.". In *Proceedings of the 33rd IEEE Conference on Decision and Control*, pages 1735–1740, Lake Buena Vista, Florida, 1994.

[55] H. Hjalmarsson, M. R. Gevers, F. De Bruyne, and J. Leblond. Identification for control: Closing the loop gives more accurate controllers. In *Proceedings of the 33rd IEEE Conference on Decision and Control*, pages 4150–4155, Lake Buena Vista, Florida, 1994.

[56] A. Helmersson. Model reduction using LMIs. In *Proceedings of the 33rd IEEE Conference on Decision and Control*, pages 3217–3222, Lake Buena Vista, Florida, 1994.

[57] B. M. Ninness and F. Gustafsson. A general construction of orthonormal bases for system identification. In *Proceedings of the 33rd IEEE Conference on Decision and Control*, pages 3388–3393, Lake Buena Vista, Florida, 1994.

[58] J. Homer, I. Mareels, B. Wahlberg, F. Gustafsson, and R. Bitmead. Lms estimation of sparsely parametrized channels via structural detection. In *Proceedings of the 33rd IEEE Conference on Decision and Control*, pages 257–262, Lake Buena Vista, Florida, 1994.

[59] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. "Optimality and suboptimality of iterative identification and control design schemes.". In *Proceedings of the 1995 American Control Conference*, pages 2559–2563, Seattle, Washington, 1995.

[60] Johan Gunnarsson and Jonas Plantin. Automatic synthesis for simultaneous supervision and control – a first example. In *1995 American Control Conference*, pages 3157–3162, 1995.

[61] P. Pucar and M. Millnert. Three techniques for state order estimation of hidden markov models. In *Proceedings of 1995 International Conference on Acoustics, Speech and Signal Processing*, volume 3, pages 1812–1815, Detroit, Michigan, 1995.

[62] S.T. Glad. Stabilizable regions for unstable systems with rate and amplitude bounds on the control. pages 489–492, Tahoe City, CA, USA, 1995. IFAC Symposium on Nonlinear Control Systems Design, NOLCOS'95.

[63] H. Fortell. Calculation of zero dynamics for affine mimo-systems using the Ritt algorithm. pages 364–369, Tahoe City, CA, USA, 1995. IFAC Symposium on Nonlinear Control Systems Design, NOLCOS'95.

[64] Ulf Söderman and Jan-Erik Strömberg. Switched bond graphs: Towards systematic composition of computational models. In *Proc. Second Int. Conf. on Bond Graph Modeling (ICBGM '95)*, number 1 in SCS Simulation Series, volume 27, pages 73–79, Las Vegas, 1995.

[65] Simin Nadjm-Tehrani and Jan-Erik Strömberg. From physical modelling to compositional models of hybrid systems. In *Proc. Formal Techniques in Real-Time and Fault-Tolerant Systems*, number 863 in Lecture Notes in Computer Science, pages 583–604, Lübeck, 1994. Springer Verlag.

[66] Simin Nadjm-Tehrani and Jan-Erik Strömberg. Modelling and Formal Analysis of an Aircraft Landing Gear System. In *Proc. of the 2nd. European workshop on Real-time and Hybrid Systems*, pages 239–246. VERIMAG Laboratory, Grenoble, May 1995.

[67] I. Renhorn, C. Karlsson, D. Letalick, M. Millnert, and R. Rutgers. Coherent laser radar for vibrometry: Robust design and adaptive signal processing. volume 2472 of *Applied Laser Radar Technology II*, Orlando, FL, April 1995. SPIE.

[68] I. Klein, P. Jonsson, and C. Bäckström. Automatic synthesis of control programs for an assembly line. In *Robotikdagarna 1995*, 1995.

Appendix H

Technical Reports

[69] J. Sjöberg. Some examples of identification with neural networks. Technical Report LiTH-ISY-R-1650, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[70] J. Gunnarsson and J. Plantin. Control law synthesis for a discrete event system. Technical Report LiTH-ISY-R-1651, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[71] L. Ljung. From data to model: A guided tour of system identification. Technical Report LiTH-ISY-R-1652, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[72] S. Gunnarsson and H. Hjalmarsson. Some aspects of iterative identification and control design schemes. Technical Report LiTH-ISY-R-1653, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[73] Ke Wang Chen. Convergence of the riccati differential equation. Technical Report LiTH-ISY-R-1660, Dept. of EE, Linköping University, 1995.

[74] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. A convergent iterative restricted complexity control design scheme. Technical Report LiTH-ISY-R-1662, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[75] L. Ljung. Aspects on accelerated convergence in stochastic approximation schemes. Technical Report LiTH-ISY-R-1663, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[76] L. Guo and L. Ljung. Performance analysis of general tracking algorithms. Technical Report LiTH-ISY-R-1664, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[77] L. Guo and L. Ljung. The role of model validation for assessing the size of the unmodelled dynamics. Technical Report LiTH-ISY-R-1665, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[78] K. Forsman and L. Habets. Input-output equations and observability for polynomial delay systems. Technical Report LiTH-ISY-R-1666, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[79] Fredrik Gustafsson. Test drives for tire-road friction estimation. Technical Report LiTH-ISY-R-1667, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[80] F. Gustafsson and N. Ninness. Asymptotic power and the gain of under-modelling in change detection. Technical Report LiTH-ISY-R-1668, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[81] F. Gustafsson. A change detection and segmentation toolbox for matlab. Technical Report LiTH-ISY-R-1669, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[82] B. M. Ninness and F. Gustafsson. A unifying construction of orthonormal bases for system identification. Technical Report LiTH-ISY-R-1670, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[83] F. Gustafsson. The marginalized likelihood ratio test for detecting abrupt changes. Technical Report LiTH-ISY-R-1671, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[84] F. Gustafsson. Segmentation of signals using piecewise constant linear regression models. Technical Report LiTH-ISY-R-1672, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[85] F. Gustafsson. Determining the initial states in forward-backward filtering. Technical Report LiTH-ISY-R-1673, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[86] H. Hjalmarsson, M. Gevers, F. De Bruyne, and J. Leblond. For model based control design, closed loop identification gives better performance. Technical Report LiTH-ISY-R-1679, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[87] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. Model free data driven optimal tuning of controller parameters. Technical Report LiTH-ISY-R-1680, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[88] T. McKelvey, H. Akcay, and L. Ljung. Identification of infinite dimensional systems from frequency response data. Technical Report LiTH-ISY-R-1681, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[89] T. McKelvey and H. Akcay. A non-iterative state-space identification algorithm. Technical Report LiTH-ISY-R-1682, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[90] H. Hjalmarsson. Model free tuning of controllers: Experience with time-varying linear systems. Technical Report LiTH-ISY-R-1683, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[91] S. T. Glad. Stabilizable regions for unstable systems with rate and amplitude bounds on the control. Technical Report LiTH-ISY-R-1684, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[92] S. T. Glad. An algebraic approach to bang-bang control. Technical Report LiTH-ISY-R-1685, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[93] S. T. Glad. Nonlinear control theory. Technical Report LiTH-ISY-R-1686, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[94] K. Wang Chen. Characterization of the riccati equation solutions via one transformation matrix. Technical Report LiTH-ISY-R-1687, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[95] A. Helmersson. Applications of mixed μ-synthesis using the passivity approach. Technical Report LiTH-ISY-R-1688, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[96] A. Helmersson. A finite frequency method for μ-analysis. Technical Report LiTH-ISY-R-1689, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[97] A. Helmersson. Model reduction from an H_∞/LMI perspective. Technical Report LiTH-ISY-R-1690, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[98] A. Helmersson. μ synthesis and LFT gain scheduling with mixed uncertainties. Technical Report LiTH-ISY-R-1691, Dept of EE. Linköping University, S-581 83 Linköping. Sweden, 1994.

[99] Predrag Pucar and Mille Millnert. Three techniques for state order estimation of hidden markov models. Technical Report LiTH-ISY-R-1703, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[100] Håkan Hjalmarsson. Asymptotic correct correlation tests in model validation. Technical Report LiTH-ISY-I-1704, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[101] H. Akcay, H. Hjalmarsson, and L. Ljung. On the choice of norms in system identification. Technical Report LiTH-ISY-R-1705, Department of Electrical Engineering, Liköping University, Sweden, 1995.

[102] H. Hjalmarsson and L. Ljung. A unifying view of disturbances in identification. Technical Report LiTH-ISY-R-1706, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[103] H. Hjalmarsson. Asymptotic correct correlation tests in model validation. Technical Report LiTH-ISY-R-1707, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[104] H. Hjalmarsson. A model variance estimator. Technical Report LiTH-ISY-R-1708, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[105] F. Gustafsson, S. Gunnarsson, and L. Ljung. On time-frequency resolution of signal properties using parameteric techniques. Technical Report LiTH-ISY-R1709, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[106] S. S. Niu, D. G. Fisher, L. Ljung, and S. L. Shah. A tutorial on multiple model least-squares and augmented ud identification. Technical Report LiTH-ISY-R-1710, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[107] S. S. Niu and L. Ljung. Multiple model parameter estimation. Technical Report LiTH-ISY-R-1711, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[108] S.S. Niu, L. Ljung, and Å. Björk. Decomposition methods for least-squares parameter estimation. Technical Report LiTH-ISY-R-1712, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[109] S. S. Niu and P. Pucar. Hinging hyperplanes for non-linear identification. Technical Report LiTH-ISY-R-1713, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[110] A. Helmersson. μ synthesis and LFT gain scheduling with time varying mixed uncertainties. Technical Report LiTH-ISY-R-1714, Department of Electrical Engineering, Linköping University, Sweden, 1995.

[111] Klein I, P. Jonsson, and C. Bäckström. Tractable planning for an assembly line. Technical Report LiTH-ISY-R-1717, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[112] R. Germundsson, J. Gunnarsson, and J. Plantin. Symbolic algebraic discrete systems - applied to the jas 39 fighter aircraft. Technical Report LiTH-ISY-R-1718, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1994.

[113] P. Pucar and J. Sjöberg. On the hinge finding algorithm for hinge hyperplanes. Technical Report LiTH-ISY-R-1720, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[114] Ke Wang Chen. Symbolic solutions of the algebraic riccati equations. Technical Report LiTH-ISY-R-1721, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[115] David-Pieter Molenaar. Model free data driven optimal tuning of controller parameters - a practical guide with application examples. Technical Report LiTH-ISY-R-1722, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[116] H. Fortell. Zero dynamics and the ritt algorithm: The MIMO-case. Technical Report LiTH-ISY-R-1723, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[117] F. Gustafsson and B. Wahlberg. Blind equalization by direct examination of the input sequences. Technical Report LiTH-ISY-R-1724, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[118] J. Homer, B. Wahlberg, and F. Gustafsson. Improved LMS estimation via structural detection. Technical Report LiTH-ISY-R-1725, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[119] U. Söderman, J.-E. Strömberg, and J. Top. Mode invariant modelling. Technical Report LiTH-ISY-R-1726, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[120] P. Pucar and J. Sjöberg. Parameterization and conditioning of hinging hyperplane models. Technical Report LiTH-ISY-R-1727, Department of EE, Linköping University, S-581 83 Linköping, Sweden, 1995.

[121] A. Helmersson. An uncertainty augmentation approach to varying μ analysis. Technical Report LiTH-ISY-R-1731, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[122] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. Optimality and suboptimality of iterative identification and control design schemes. Technical Report LiTH-ISY-R-1733, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[123] L. Ljung. System identification. to be included in modern control systems - a self study course, edited by m. masten. Technical Report LiTH-ISY-R-1735, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[124] H. Fortell. Some notes on sliding mode control and the ritt algorithm. Technical Report LiTH-ISY-R-1736, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[125] H. Fortell. A generalized normal form and its application to sliding mode control. Technical Report LiTH-ISY-R-1737, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[126] H. Fortell. A normal form for generalized state space descriptions. Technical Report LiTH-ISY-R-1738, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[127] U. Söderman and J-E Strömberg. Switched bond graphs: Towards systematic composition of computational models. Technical Report LiTH-ISY-R-1739, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[128] U. Söderman and J-E Strömberg. Switched bond graphs: Multiport switches, mathematical characterization and systematic composition of computational models. Technical Report LiTH-ISY-R-1740, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[129] P. Lindskog and J. Sjöberg. A comparison between semi-physical and black-box neural net modeling: A case study. Technical Report LiTH-ISY-R-1741, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[130] J. Sjöberg, Q. Zhang, L. Ljung, A. Benveniste, B. Deylon, P-Y Glorennec, H. Hjalmarsson, and A. Juditsky. Nonlinear black-box modeling in system identification: a unified overview. Technical Report LiTH-ISY-R-1742, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[131] A. Juditsky, H. Hjalmarsson, A. Benveniste, B. Delyon, L. Ljung, J. Sjöberg, and Q. Zhang. Nonlinear black-box modeling in system identification: Mathematical foundations. Technical Report LiTH-ISY-R-1743, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[132] H.R. Rutgers. Parameter estimation in vibrometry data. Technical Report LiTH-ISY-R-1745, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[133] I. Klein, Peter Jonsson, and Christer Bäckström. Tractable correct planning for an assembly line. Technical Report LiTH-ISY-R-1746, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[134] R. Germundsson. Symbolic algebraic discrete systems: Theory and computation. Technical Report LiTH-ISY-R-1747, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[135] R. Germundsson and T. Glad. A unified constructive study of linear, nonlinear and discrete event systems. Technical Report LiTH-ISY-R-1748, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[136] R. Germundsson. Verifying temporal properties in discrete event systems. Technical Report LiTH-ISY-R-1749, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[137] P. Pucar and M. Millnert. Smooth hinging hyperplanes - an alternative to neural nets. Technical Report LiTH-ISY-R-1750, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[138] S. Nadjm-Tehrani and J.-E. Strömberg. Modelling and formal analysis of an aircraft landing gear system. Technical Report LiTH-ISY-R-1751, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[139] L. Ljung and T. McKelvey. Subspace identification methods for closed loop input-output data. Technical Report LiTH-ISY-R-1752, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[140] F. Gustafsson and B. M. Ninness. Asymptotic power and the benefit of under-modeling in change detection. Technical Report LiTH-ISY-R-1753, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[141] F. Gustafsson and S. F. Graebe. Closed loop performance monitoring in the presence of system changes and disturbances. Technical Report LiTH-ISY-R-1754, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[142] F. Gustafsson. Slip-based estimation of tire - road friction. Technical Report LiTH-ISY-R-1755, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[143] H. Hjalmarsson, S. Gunnarsson, and M. Gevers. Model free tuning of a robust regulator for a flexible transmission system. Technical Report LiTH-ISY-R-1757, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[144] H. Hjalmarsson. Model free tuning of controllers: Experience with time-varying linear systems. Technical Report LiTH-ISY-R-1758, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[145] L. Ljung. System identification, to be included in the control handbook, edited by w. levine. Technical Report LiTH-ISY-R-1763, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[146] I. Renhorn, C. Karlsson, D. Letalick, M. Millnert, and R. Rutgers. Coherent laser radar for vibrometry: Robust design and adaptive signal processing. Technical Report LiTH-ISY-R-1764, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[147] T. McKelvey. Frequency domain identification, subspace methods and periodic excitation. Technical Report LiTH-ISY-R-1765, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[148] L. Ljung. Nonlinear black-box modeling in system identification. Technical Report LiTH-ISY-R-1770, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[149] H. Fortell. On the generalized normal form for MIMO-systems. Technical Report LiTH-ISY-R-1771, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[150] T. McKelvey. Model validation by geometric arguments. Technical Report LiTH-ISY-R-1772, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[151] T. McKelvey, T. Abrahamsson, and L. Ljung. Vibration data analysis for a commercial aircraft. Technical Report LiTH-ISY-R-1773, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[152] T. McKelvey. Asymptotic variance expressions for a frequency domain subspace based system identification algorithm. Technical Report LiTH-ISY-R-1774, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[153] T. McKelvey. Frequency domain system identification with IV based subspace algorithm. Technical Report LiTH-ISY-R-1775, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[154] T. McKelvey. Frequency weighted subspace based system identification in the frequency domain. Technical Report LiTH-ISY-R-1776, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 1995.

[155] Roger Germundsson, Johan Gunnarsson, Arne Jansson, Petter Krus, Magnus Morin, Simin Nadjm-Tehrani, Jonas Plantin, Magnus Sethson, and Jan-Erik Strömberg. Complex hybrid systems I: a study of available tools and specification of planned work. Technical Report LiTH-IDA-R-94-29, Dept. of Computer Science, Linköping University, S-581 83 Linköping, Sweden, June 1994.

Appendix I

Master Theses (Examensarbeten)

[156] Mikael Åslund. Simulator for testing the control system of the handling machine for handling of spent nuclear fuel. Master Thesis LiTH-ISY-EX-1530, Dept of EE. Linköping University, 950310.

[157] Torbjörn Ahnell and Fredrick Andersson. Development of signal processing functions for a sonar system. Master Thesis LiTH-ISY-EX-1538, Dept of EE. Linköping University, 950331.

[158] Fredrik Almyren. Investigation of Synchronization in SDH networks –Generation, Verification and Simulation of synchronization plans. Master Thesis LiTH-ISY-EX-1472, Dept of EE. Linköping University, 941219.

[159] Fredrick Andersson and Torbjörn Ahnell. Development of signal processing functions for a sonar system. Master Thesis LiTH-ISY-EX-1538, Dept of EE. Linköping University, 950331.

[160] Magnus Andersson and Urban Blomberg. Path planning –a study with rectilinear paths among elliptical obstacles. Master Thesis LiTH-ISY-EX-1523, Dept of EE. Linköping University, 941221.

[161] Niclas Anehill and Anders Bogren. A model of the control of the synchronization in telephone exchange AXE-10. Master Thesis LiTH-ISY-EX-1437, Dept of EE. Linköping University, 940909.

[162] Francesco Barbariol. Implementation of an autonomous helicopter flight control. Master Thesis LiTH-ISY-EX-1618, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 950606.

[163] Joakim Berg. Position control and test of an attitude controlled autonomous miniature helicopter. Master Thesis LiTH-ISY-EX-1554, Dept of EE. Linköping University, 950220.

[164] Hans-Olof Berlin. Near-field Radar cross section measurement. Master Thesis LiTH-ISY-EX-, Dept of EE. Linköping University, 941221.

[165] Urban Blomberg and Magnus Andersson. Path planning –a study with rectilinear paths among elliptical obstacles. Master Thesis LiTH-ISY-EX-1523, Dept of EE. Linköping University, 941221.

[166] Lars Blomström and Anders Eriksson. State-space neural networks. Master Thesis LiTH-ISY-EX-1454, Dept of EE. Linköping University, 950519.

[167] Anders Bogren and Niclas Anehill. A model of the control of the synchronization in telephone exchange AXE-10. Master Thesis LiTH-ISY-EX-1437, Dept of EE. Linköping University, 940909.

[168] Jonas Bolander. Segmentation Algorithms for Laser Radar Images. Master Thesis LiTH-ISY-EX-1352, Dept of EE. Linköping University, 950421.

[169] Anders Brandt. Control of an unstable missile. Master Thesis LiTH-ISY-EX-1540, Dept of EE. Linköping University, 941221.

[170] Royne Carlsson. Interpolation in laser radar images by wavelet-technique. Master Thesis LiTH-ISY-EX-1556, Dept of EE. Linköping University, 950609.

[171] Anders Doverfors. A verification model in NP-circuit for a part of the fuel system in test aircraft JAS39 Gripen. Master Thesis LiTH-ISY-EX-1453, Dept of EE. Linköping University, 941202.

[172] Anders Ericsson. Metalldetektor med digital signalbehandling. Master Thesis LiTH-ISY-EX-1483, Dept of EE. Linköping University, 941104.

[173] Anders Eriksson and Lars Blomström. State-space neural networks. Master Thesis LiTH-ISY-EX-1454, Dept of EE. Linköping University, 950519.

[174] Pär Eriksson. Modelling and forecasting of weatherdependent sales. Master Thesis LiTH-ISY-EX-1482, Dept of EE. Linköping University, 941020.

[175] Peter Fagerström. Development of test system for the control system in MasterPiece 200/1. Master Thesis LiTH-ISY-EX-1517, Dept of EE. Linköping University, 950609.

[176] Niklas Fransson. Control of an Inverted Pendulum with a Data Acquisition Processor. Master Thesis LiTH-ISY-EX-1552, Dept of EE. Linköping University, 950529.

[177] Elisabeth Gustafsson. Fuzzycontroll of the watersystem in Ringhals 1. Master Thesis LiTH-ISY-EX-1470, Dept of EE. Linköping University, 940918.

[178] Carl Johan Håkansson and Lars Norden. Ship automation –a guide to the market. Master Thesis LiTH-ISY-EX-1533, Dept of EE. Linköping University, 950202.

[179] Anna Hagenblad. Chaos tests as a preliminary step in the analysis of time series. Master Thesis LiTH-ISY-EX-1579, Dept of EE. Linköping University, 950323.

[180] Fredrik Hansson and Tomas Jagborn. Control strategy of an auxiliary converter to limit current when connecting an induction motor. Master Thesis LiTH-ISY-EX-1515, Dept of EE. Linköping University, 950227.

[181] Tomas Jagborn and Fredrik Hansson. Control strategy of an auxiliary converter to limit current when connecting an induction motor. Master Thesis LiTH-ISY-EX-1515, Dept of EE. Linköping University, 950227.

[182] Niklas Johansson and Mikael Strömsöe. Quality driven channel selection and power control in PDC. Master Thesis LiTH-ISY-EX-1532, Dept of EE. Linköping University, 950522.

[183] Christer Jonasson. Analysis and implementation of digital control algorithms in a radiation exposure meter. Master Thesis LiTH-ISY-EX-1572, Dept of EE. Linköping University, 950608.

[184] Jonas Karlsson and Jan Rögde. Simulation Tool for Development of Control Strategies for PFBC-Power Plants. Master Thesis LiTH-ISY-EX-1563, Dept of EE. Linköping University, 950608.

[185] Gunilla Larsson. Towards a dynamic model for the cryogenics of the superconducting cavity module. Master Thesis LiTH-ISY-EX-1513, Dept of EE. Linköping University, 950426.

[186] Krister Larsson. Tactical aeroplane control by fuzzy logic. Master Thesis LiTH-ISY-EX-1490, Dept of EE. Linköping University, 941025.

[187] Magnus Larsson. Aerodynamic model identification with extended Kalman and artificial neural nets using the EBM method. Master Thesis LiTH-ISY-EX-1576, Dept of EE. Linköping University, 950330.

[188] Tomas Lindqvist. Diesel Engine Simulation. Technical Report LiTH-ISY-EX-1465, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 940916.

[189] Maria Lindström and Johanna Persson. Linear and Non-Linear Identification of the Energy Efficiency for an Electric Arc Furnace. Master Thesis LiTH-ISY-EX-1525, Dept of EE. Linköping University, 950524.

[190] Camilla Luck and Henrik Wester. Identification and verification of process model for submerged arc welding. Master Thesis LiTH-ISY-EX-1534, Dept of EE. Linköping University, 950515.

[191] Jonas Mikaelsson. Indoor climate control using Fuzzy Logic. Master Thesis LiTH-ISY-EX-1519, Dept of EE. Linköping University, 941210.

[192] David-Pieter Molenaar. Model Free Data Dirven Optimal Tuning of Controller Parameters -A Practical guide with application examples. Master Thesis LiTH-ISY-R-1722, Dept of EE. Linköping University, 950213.

[193] Lars Norden and Carl Johan Håkansson. Ship automation –a guide to the market. Master Thesis LiTH-ISY-EX-1533, Dept of EE. Linköping University, 950202.

[194] David Olsson. Simulation of Laser Bathymetri. Master Thesis LiTH-ISY-EX-1509, Dept of EE. Linköping University, 940916.

[195] Magnus Olsson. Prediction and visualization of traffic in cellular mobile telephone systems. Master Thesis LiTH-ISY-EX-1473, Dept of EE. Linköping University, 941216.

[196] Johanna Persson and Maria Lindström. Linear and Non-Linear Identification of the Energy Efficiency for an Electric Arc Furnace. Master Thesis LiTH-ISY-EX-1525, Dept of EE. Linköping University, 950524.

[197] Martin Persson. Multivariable feedback design simultaneously in time and frequency domain via convex optimization. Master Thesis LiTH-ISY-EX-1452, Dept of EE. Linköping University, 940902.

[198] Jan Rögde and Jonas Karlsson. Simulation Tool for Development of Control Strategies for PFBC-Power Plants. Master Thesis LiTH-ISY-EX-1563, Dept of EE. Linköping University, 950608.

[199] Fabio Russian. Automatic Generation of Control Programs for an Assembly Line. Master Thesis LiTH-ISY-EX-1620, Dept of EE. Linköping University, 950622.

[200] Hermina Regina (Remke) Rutgers. Parameter estimation in vibrometry data. Master Thesis LiTH-ISY-R-1745, Dept of EE. Linköping University, 950426.

[201] Anders Skytt. Remote diagnostics/supervision. Master Thesis LiTH-ISY-EX-1531, Dept of EE. Linköping University, 950315.

[202] Johan Stake. A behavioral description of Intel's 80486 microprocessor. Master Thesis LiTH-ISY-EX-1390, Dept of EE. Linköping University, 941213.

[203] Mikael Strömsöe and Niklas Johansson. Quality driven channel selection and power control in PDC. Master Thesis LiTH-ISY-EX-1532, Dept of EE. Linköping University, 950522.

[204] Daniel Troedsson. Estimation of Heat Condution Equation Parameters. Master Thesis LiTH-ISY-EX-1568, Dept of EE. Linköping University, 950214.

[205] Henrik Wester and Camilla Luck. Identification and verification of process model for submerged arc welding. Master Thesis LiTH-ISY-EX-1534, Dept of EE. Linköping University, 950515.