LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
JULY 1995 - DECEMBER 1996

Contents

Chapter 1

Introduction

The Swedish government institutions have changed their fiscal years to coincide with the calender years. As a consequence, our department had a fiscal year stretching from July 1, 1995 to December 31, 1996. We have decided to let our annual reports be synchronized with this. Hence we cover 18 months of activities in the present report.

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 Modeling 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, to theoretical aspects in how to evaluate model quality in the presence of under-modeling.

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

We thank the Swedish Research Council for Engineering Sciences (TFR), the Swedish National Board for Industrial and Technical Development (NUTEK) and the Foundation for Strategic Research (SSF) for funding a major part of our research.

A major event during the year was the start of the NUTEK Competence Center ISIS (Information Systems for Industrial Control and Supervision). The Automatic Control group plays an active role in this center, and it will be further described in the next section.

Another important event was that the Research School ECSEL (Excellence Center for Computer Science and Systems Engineering in Linköping) started its activities during 1996. This research school is funded by the Foundation for Strategic Research (SSF) and is a joint effort between the departments of Electrical Engineering and Computer Science. Again, the Control Division is a central partner in this venture.

Five of our graduate students have defended their Ph.D. theses during the year: Roger Germundsson, Håkan Fortell, Predrag Pucar, Anders Helmersson and Peter Lindskog. Moreover Anders Ericsson, Mats Jirstrand and Krister Edström finished their Tekn. Lic. degrees.

An honorary doctors degree was conferred on Lennart Ljung by the Baltic State Technical University in S:t Petersburg, Russia. He was also awarded the Chester Carlson Prize.

In the following pages the main research results obtained during the 18 month fiscal year 1995/96/96 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.

The competence center ISIS has the home page

`http://vir.liu.se/isis`

and for the research school ECSEL turn to

`http://vir.liu.se/ecsel`

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.

[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.

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`

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, Mattias Olofsson:

`mattiaso@isy.liu.se`

Chapter 3

The Competence Center ISIS

ISIS - **I**nformation **S**ystems for **I**ndustrial Control and **S**upervision (**I**ntegrerade **S**tyr- och **I**nformations**S**ystem) is a coalition between seven companies:

- ABB Industrial Systems
- ABB Robotics
- Ericsson Development AB
- Mecel AB
- SAAB Automobile
- SAAB Dynamics
- SAAB Military Aircraft

and five research groups at Linköping School of Engineering (LiTH)

- Division of Automatic Control
- Division of Vehicular Systems
- Laboratory for Engineering Data Bases (EDSLAB)
- Laboratory for Real Time Systems (RTSLAB)
- Laboratory for Representation of Knowledge (RKLLAB)

Figure 3.1: From the inauguration of ISIS, Lennart Ljung and Bengt Halse, President of Saab AB, one of the main speakers at the inauguration.

It is funded by NUTEK, by LiTH and by the participating companies.

The Center started November 1, 1995, and had an opening seminar on April 19, 1996.

The main work of the center concerns the *projects*, which during the first year have been:

1. Real-Time Data Bases for Telecommunication
2. Databases for Integrated Navigation Systems
3. Diagnosis for Car Engines
4. Verification Automation in Software Development
5. Enhancement of Process Control Languages
6. Navigation Systems
7. Supervision and Control of Industrial Robots

In addition ISIS runs company-specific groups for direct and non-project-related contacts with the industrial partners. ISIS also has a bi-weekly seminar series, with half-day workshops organised about every second month.

ISIS is governed by a board consisting of

- Ulf Rehme, SAAB AB (chairman)
- Staffan Ahlinder, ABB Industrial Systems
- Hans Alberg, Ericsson Development
- Jan Nytomt, MECEL
- Erik Sandewall, LiTH

The general manager of ISIS is Lennart Ljung.

Chapter 4

System Identification

4.1 Introduction

The research in System Identification covers a rather wide spectrum, from general principles to particular applications.

Peter Lindskog finished his PhD-thesis, [5], on how to make use of prior knowledge in system identification. See Section 4.3 for more details. Part of Predrag Pucar's PhD-thesis, [2], deals with non-linear black-box model structures built from hinging hyperplanes.

Together with IRISA at Rennes, we have finished a broad overview of non-linear black box models, such as Neural Networks, Hinging Hyperplanes and Fuzzy Modeling, [15], [16]. Related expositions are given in [29], [33], [30] and [52].

Some general expositions about the system identification problem include [76] for a historical review, and [90] for connections between PAC-learning and system identification.

4.2 Linear Models

4.2.1 Orthonormal bases for system identification

In the conference paper [49] we investigate the properties of a simple but very general construction for complete orthonormal bases for system identification. In the construction, one chooses the poles (real or complex-conjugated) in the basis functions, and the orthonormalization is given by:

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

It has been 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:

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

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.

In [49] a novel proof technique is used to show that the asymptotic variance of the transfer function is given by

$$\mathrm{Cov}(\hat{G}_{p,N}(\omega)) = \frac{\sum_{k=0}^{p-1} |\mathcal{B}_k(e^{i\omega})|^2}{N} \frac{\Phi_e(\omega)}{\Phi_u(\omega)}$$

In contrast to the well-known result using black-box model structures we here have to replace the constant p (model order) by the frequency weighting $|\sum_{k=0}^{p-1} \mathcal{B}_k(e^{i\omega})|^2$, that depends on the chosen poles and this equals to p in the (frequency) average. Rather surprisingly, this shaping function appears also in black-box modeling whenever a prefilter of the same order as the model is used.

As an illustration, consider an experiment where 2048 measurements $y(t)$ of flight flutter of a specific aircraft component are collected when excited by a test signal $u(t)$[1]. The interesting frequency range is between 4 and 11 Hertz, where a band-pass filter is applied to the original data. The twelve poles in the basis construction are chosen as follows:

$$\begin{aligned} p_i &= 0.73,\ 0.73,\ 0.73,\ 0.73, \\ &\quad 0.930 \pm i0.298,\ 0.906 \pm i0.363,\ 0.886 \pm i0.411,\ 0.844 \pm i0.505 \end{aligned}$$

[1]These data are presented in J.Schoukens and R.Pintelon, *Identification of linear systems. A practical guideline to accurate modeling*, Pergamon Press U.K. 1991

The complex conjugated poles are obtained from a spectral analysis showing four dominating oscillations. The left plot of Figure 4.1 shows the estimated frequency response together with a spectral estimate. The model has apparently caught most of the dynamics in the system. As comparison, the right plot shows the result using high order output error structures of type: general black box (`oe` of order 20), Laguerre with 20 poles at 0.73 and Kautz model where the 4 complex poles are repeated 3 times yielding 24 parameters. These all give quite poor result.

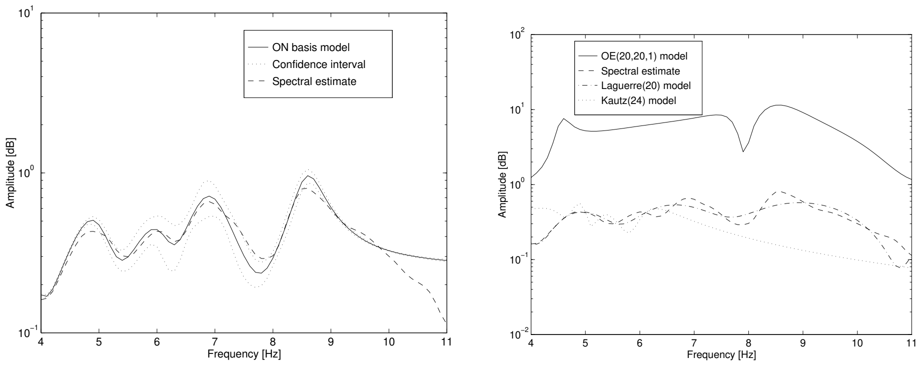


Figure 4.1: Transfer function estimate from non-parametric method and parametric model. Left: ON basis model structure with 12 parameters. Right: three standard model structures.

The point with this example is that the rather high model order (12) makes the conditions for the asymptotic variance expression plausible. That is, we can compute confidence bounds on the transfer function estimate. The confidence bound in the amplitude plot of Figure 4.1 reflects the fact that by our choice of poles we aim at minimizing the bias error between 5 and 9 Hertz and thus we have to accept a large variance error. Outside this frequency interval, the variance error is negligible while the bias error is large. This explains the “incorrect” confidence interval between 9 and 11 Hertz.

4.2.2 Identification and Controller Design

A method for tuning the parameters ρ of a controller by minimizing a criterion of the type

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

has been studied. Here $\tilde{y}(\rho)$ denotes the difference between the real output and the output of a reference model T_d, and L_y and L_u denote filters which can be used to give different frequency ranges of the signals different weight. 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. The method has successfully been applied to a benchmark problem proposed for the 1995 European Control Conference, and the results are presented in [9] and [42].

4.2.3 Recursive identification

Using recursive identification with some kind of forgetting mechanism the algorithm becomes sensitive for poor excitation in signals. Several methods for dealing with this problem have been proposed, and in [96] it is shown that some of these methods can be interpreted as an approximate regularization of the information matrix.

The standard problem of estimating the time-varying parameters $\theta(t)$ of a linear regression is given by

$$y(t) = \varphi^T(t)\theta(t) + e(t) \tag{4.2}$$

and the basic estimation 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 [13] 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 [14]. Necessary and sufficient stability conditions for the special, common LMS-algorithm are given in [18].

4.2.4 Periodic excitation signals

The use of periodic excitation signals offers some nice advantages over conventional non-periodic signals. In the papers [23, 39, 34] a subspace based algorithm is presented which is based on use of a periodic excitation signal. By explicitly taking advantage of the periodicity, the computational complexity of the algorithm is several orders of magnitude lower than conventional methods. Since the excitation is periodic the output of the system also becomes periodic (asymptotically). This enables simple averaging over the periods as a mean of data compression and noise reduction prior to fitting a rational model. In the paper [74] the idea is further pursued by considering the identification of a plant in a closed loop using noisy measurements of both the input and output of the system. Normally, when the input is measured with noise, the general identification problem becomes quite difficult. However if the closed loop system is excited with a periodic signal, the system can be consistently identified without the knowledge of the controller and for a large class of noise sources including noise of arbitrary color. As long as the plant is stabilized by the controller, unstable plants can also be handled.

4.2.5 Subspace based identification methods

Analysis of time domain methods

The so-called subspace methods for direct identification of linear models in state space form have drawn considerable interest recently. They have been found to work well in many cases but have one drawback - they do not yield consistent estimates for data collected under output feedback. The reason for this is shown in the paper [11] by considering the estimation of the state-space variables as k-step ahead output predictors. By recomputing these from a non-parametric one-step ahead predictor model, consistency can be achieved also for closed loop data.

The subspace methods consists of a series of quite complex projections, and it is not easy to intuitively understand how they work. In the conference paper [87] an interpretation of the subspace methods is given based on a least-squares view. In particular it is shown that consistent estimates can be obtained although the correct predictors are not used.

Frequency domain methods

Frequency domain identification, i.e. when samples of the transfer function is considered as primary measurements, recently has attracted some interest. Various aspects of prefiltering are more easily understood and implemented in the frequency domain. In the paper [26] some subspace based algorithms for multivariable frequency domain identification are proposed. Analysis with respect to consistency is performed illustrating the practical requirements of the algorithms. Promising results are obtained with the algorithms when applied to real frequency data from a large flexible structure.

For the case when the system identification algorithm is applied to an infinite dimensional system a low-complexity model results. Analysis in [25, 38] reveals that, under certain conditions, the algorithm converges to the balanced truncation of the system.

For reasons of accuracy comparison, the asymptotic variance of a frequency domain subspace algorithm is derived in [55]. It is shown that the transfer function estimate is asymptotically normal and an expression of the variance is derived. By comparing the variance expression with the Cramér-Rao lower bound it is concluded that the method is variance sub-optimal.

By introducing certain matrix weights in the subspace algorithm the frequency distribution of the resulting fitting error can be controlled. In [56] this idea is investigated and a small illustrating example is presented.

Realization of rational matrix functions from given data plays an important role in the $\mu-$analysis and synthesis of robust controllers. In [88] a practical algorithm based on subspace based identification and parametric optimization is presented for approximation of non-diagonal matrix scalings used in the $D - K$ synthesis algorithm.

4.2.6 Non-minimal parametrizations of multivariable linear system

Multivariable parametric identification always involves a choice of model structure besides the determination of model order if a minimal parametrization is used. By considering parametrizations of state-space models which are overparametrized, i.e. have more parameters than the minimal parametrization, only a single model structure needs to be considered. In the paper [24] it is shown that Cramér-Rao lower bound of the variance of the estimated model using an overparametrized model structure equals the bounds of a minimal parametrization.

A new non-minimal parametrization of multivariable linear systems based on a compact tridiagonal matrix form is presented in [68, 89]. It is shown that all multivariable systems of a given order can be described in this parametrization. The proof consists of showing that any square real matrix is similar to the proposed tridiagonal matrix form. Since the parametrization is based on the numerically stable tridiagonal matrix form, models of high order can be estimated with high accuracy.

Model Validation

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], [17], [12] and [77] it is shown how "classical" model validation tests, in terms of cross-correlation functions between residuals and past inputs, give explicit expressions for the discrepancy between the estimated and the true frequency functions.

The basic result can be formulated as follows:

$$\begin{aligned} &\left[\frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\tilde{G}(e^{i\omega})\right|^2\left|L(e^{i\omega})\right|^2|U_N(\omega)|^2\,d\omega\right]^{1/2} \leq \\ &\leq \quad (1+\eta)\left[\frac{1}{N}\tilde{\xi}_N^M\right]^{1/2} + (1+\eta)x_N + (2+\eta)C_u\sum_{k=M}^{\infty}|\rho_k| \end{aligned} \tag{4.3}$$

Here

- G_0 is a "true" description relating the input and output sequences by $y = G_0u + v$, for any sequence v.
- $\tilde{G} = \hat{G} - G_0$, where $\hat{G}$ is any model.
- ε is the model residual $\varepsilon = L(q)(y - \hat{G}u)$ and $\tilde{\xi}$ is the standard model validation quantity

  $$\tilde{\xi}_N^M = \frac{1}{N}\left\|\sum_{t=1}^{N}\varphi(t)\varepsilon(t)\right\|_{R_N^{-1}}^2 \tag{4.4}$$

  with

  $$\varphi(t) = [u(t-1),\dots,u(t-M)]^T$$

and

$$R_N = \frac{1}{N}\sum_{t=1}^{N}\varphi(t)\varphi^T(t) > \delta I$$

- $x_N = \left\| \frac{1}{N}\sum_{t=1}^{N}\tilde{v}(t)\varphi(t)\right\|_{R_N^{-1}}$
- $\tilde{v}(t) = L(q)v(t)$
- ρ_k is the impulse response of $L(q)\tilde{G}(q)$
- $|U_N|^2$ is the periodogram of the input:

$$|U_N(\omega)|^2 = \frac{1}{N}\left|\sum_{t=1}^{N}u(t)e^{-i\omega t}\right|^2$$

- $\eta = \frac{C_u M}{\sqrt{N\delta}}$
- $C_u = \max_{1\leq t\leq N}|u(t)|$.

The result as such basically deals with algebraic relationships between given sequences and filters. It has in itself nothing to do with probabilistic interpretations etc. See the cited references for discussions of various interpretations.

In [37] system identification is discussed from a model validation perspective: "Let us compute all those models that will pass a given validation criterion."

4.3 System identification based on prior knowledge

Don't estimate what you already know – build that into the applied model structure! This basic principle in estimation and identification, which can be thought of as a pragmatic variant of the *principle of parsimony* – to be parsimonious with the parameters to estimate – is the golden lodestar within this research project. By building structural and/or non-structural prior knowledge into the model structures one can in many practical situations obtain models that are "better" suited for their intended use.

A first approach in this direction is *semi-physical modeling*. The basic idea is to utilize physical insight about the underlying process so as to come up with certain nonlinear (and physically motivated) combinations of the raw measurements. These combinations – the new inputs and outputs – are then subjected to standard model structures (which typically are linear in the parameters and in the new variables). Some numeric and symbolic methods, algorithms and tools for pursuing semi-physical modeling are described in the journal paper [10], but is also available as a technical report [117].

The paper [35] gives a comparison between semi-physical and neural network based black box modeling. Advantages and disadvantages with these approaches are discussed based on an application example. It is also pointed out how semi-physical modeling can be used as a pre-processing step for determining the regression vector to be used as the input to a neural network predictor. In [152] we go one step further by suggesting a combined semi-physical and neural network based model structure. The main idea is to capture what is actually known about the system in question using a semi-physical model, and then describe the remaining dynamics using a "small" neural network. The usefulness of this approach is illustrated in a simple tank level modeling application.

For many real-world systems a great deal of information is provided by human experts, who do not reason in terms of mathematics but instead describe the system verbally through vague or imprecise statements, usually through if-then rules. A convenient way of taking such knowledge into account is to use fuzzy logic concepts in order to cast the verbal knowledge into a conventional mathematical representation (a model structure), which subsequently can be fine-tuned using input-output measurements. In [154] it is emphasized that the most often used structure for *fuzzy identification* is a functional series expansion of the form

$$\hat{y}(t) = g(\boldsymbol{\varphi}(t), \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}) = \sum_{j=1}^{n} \alpha_j \prod_{k=1}^{r} g_{j,k}(\varphi_k(t), \boldsymbol{\beta}_{j,k}, \boldsymbol{\gamma}_{j,k}), \tag{4.5}$$

where $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ are parameters, and the $g_{j,k}(\cdot,\cdot,\cdot)$ are one-dimensional basis functions that often are referred to as membership functions. This observation means that efficient Newton type of algorithms can be applied for parameter estimation, where, to preserve expert knowledge having minor data support, it is important to introduce a regularizing effect. Contrary to other series expansions like, e.g., one hidden layer neural networks, we here have parameters that can be linguistically interpreted. In [154] it is stressed that this knowledge easily can be lost in the estimation step, unless special parameter restrictions are imposed. This also means that constrained parameter estimation algorithms are needed.

The prior knowledge is not always of a precise, analytical character. Sometimes we only know that the step response is monotonic, or that the steady-state gain curve is monotonic in certain input variables, or some other qualitative property. The papers [151] and [154] propose one particular fuzzy model structure parameterization that combines the richness and flexibility of (4.5) with such monotonicity features. This property, which is crucial to maintain for certain applications of the model, can be preserved through constrained estimation.

An always present and relevant issue in system identification is the availability of software tools. The report [156] describes one rather general software package for performing identification experiments of the kind outlined above. This prototype package, written in MATLAB, can be downloaded from

`ftp://ftp.control.isy.liu.se/pub/Software/Fuzzy/`

4.4 Applications

4.4.1 Efficient algorithms for updating of FE models

Updating finite element (FE) models is the task of adjusting parameters in the FE model such that the properties of the model and the measured data agree. For mechanical structures data consists of either resonance frequencies and mode shapes and/or samples of the transfer function. In [80] a quadratic optimization criterion based on both the deviation of resonance frequencies as well as the deviation of the frequency response is proposed. Using an example the criterion is shown to be quasi-convex in a rather large neighborhood of the global minimum.

4.4.2 Vibration analysis and model validation

Using impulse response data from extensive vibrational tests of the Saab 2000 aircraft, se figure 4.2, a combined method for vibrational analysis is studied in [27]. The method is based on a combination of a subspace based

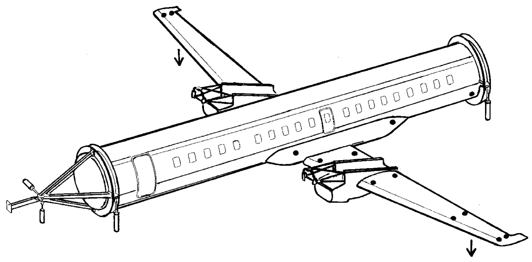


Figure 4.2: Test specimen. Location of wing and fuselage accelerometers are shown as dots (nacelle accelerometers are not shown). All shown accelerometers sense vertical accelerations. Arrows indicate location of the snap-back cables.

realization algorithm and standard prediction error methods. Figure 4.3 depicts measured accelerometer data and predictions by the estimated model. Also a new model validation criterion for impulse response data is demonstrated. The method is based on validating each mode of a model and is further analyzed in [40].

4.4.3 Recursive identification

In [51] it is shown how recursive identification can be used for control of a flexible mechanical system containing hydraulic actuators. Relevant parameters describing the dynamics of the crane are identified and used for tuning of position and pressure feed-back loops. A mechanism for impact detection using accelerometer signals is also incorporated.

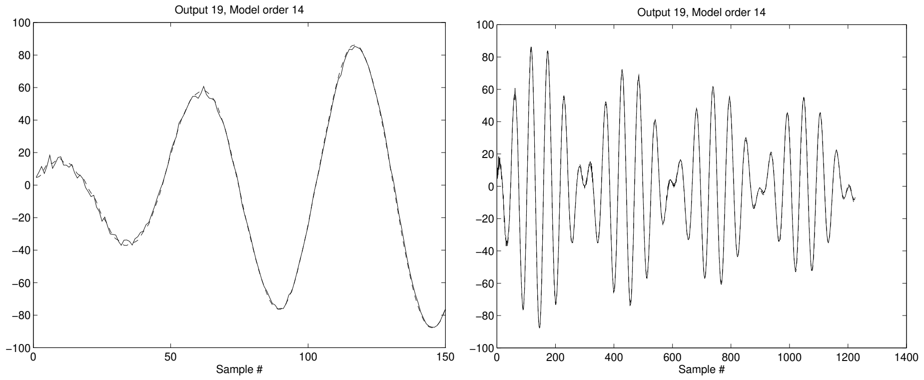


Figure 4.3: Measured (solid) and simulated (dashed) normalized accelerations of rear fuselage. The simulated outputs originate from an estimated model of order 14. Left graph is a close up of the 150 first samples of the right graph.

Chapter 5

Non-Linear Systems

5.1 Zero dynamics and normal forms

The zero dynamics of a system is the dynamics that remains when the output is kept identically at the desired value (usually assumed to be zero). If the zero dynamics is unstable it suggests that there might be difficulties in controlling the system. For linear systems the poles of the zero dynamics are the zeroes of the system (hence the name). For nonlinear systems there are established methods to calculate the zero dynamics within a differential geometric context. In [3] the zero dynamics is calculated using differential algebraic methods. This permits the extension to more general dynamic systems (not necessarily described by state space models) and extends the use of certain normal forms. The technique has implications for controller design, for instance in the use of sliding mode, [60]. As an example of zero dynamics calculations consider a VTOL aircraft. The dynamics is

$$\begin{aligned} \dot{x}_1 &= x_2, \quad & \dot{x}_2 &= -u_1 \sin x_5 \epsilon u_2 \cos x_5 \\ \dot{x}_3 &= x_4, \quad & \dot{x}_4 &= u_1 \cos x_5 \epsilon u_2 \sin x_5 - 1 \\ \dot{x}_5 &= x_6, \quad & \dot{x}_6 &= u_2 \end{aligned}$$

If x_1 and x_3 are considered as outputs the zero dynamics is

$$\dot{x}_5 = x_6, \quad \dot{x}_6 = \frac{1}{\epsilon} \sin x_5$$

which can be verified using both geometric and differential algebraic calculations. The zero dynamics is clearly unstable. In analogy with the linear case the system is said to be non-minimum phase.

5.2 Constraints in dynamic systems

Solvability of dynamic systems with inequalities

When modeling physical systems one often arrives at a mixture of equations in a number of physical variables and their derivatives. The model might only be valid for certain values of the physical variables or one might want to study it only in a certain range. This could be expressed by inequalities or inequations. An obvious question is then whether there exists a solution that satisfies all equations, inequations and inequalities. Also one would like to transform the system to some standard form which facilitates the computation of such a solution. In [136] systems of equations, inequations and strict inequalities are considered:

$$\begin{aligned} f_1 = 0, \ldots, f_n = 0, \quad g_1 \neq 0, \ldots, g_m \neq 0 \\ h_1 < 0, \ldots, h_q < 0 \end{aligned} \tag{5.1}$$

The f_i, g_i and h_i are differential polynomials in some variables $y_1, \ldots, y_N$, i. e. they are polynomials in those variables and a finite number of their derivatives. The system is reduced to a standard form in which solvability can be decided using real algebra. For example the system

$$\begin{aligned} \dot{y}_1^2 + \dot{y}_2^2 - 1 &= 0 \\ y_1 y_2 - 1 &= 0 \\ \ddot{y}_1 + \ddot{y}_2 &< 0 \end{aligned}$$

can be reduced to

$$\begin{aligned} (y_1^4 + 1)\dot{y}_1^2 - y_1^4 &= 0 \\ y_1 y_2 - 1 &= 0 \\ y_1 &\neq 0 \\ y_1^4 + 1 &\neq 0 \\ \dot{y}_1 &\neq 0 \\ y_1^{11}(y_1^2 + 1)(y_1^4 + 1)^3 &< 0 \end{aligned}$$

which is solvable since the initial value problem

$$\dot{y}_1 = \pm\sqrt{y_1^4/(y_1^4 + 1)}, \quad y_1(0) < 0, \quad y_2 = 1/y_1$$

is solvable.

An algebraic approach to bang-bang control

For many optimization criteria linear systems with bounded controls are optimally controlled using only the extreme values of control (bang-bang control). In [36] bang-bang control of systems with real poles was considered. It was shown that the calculation of a control to reach a certain point is a real algebraic problem provided the ratios of the poles are rational numbers.

Stabilization under constraints

In many control problems the actuator constraints can be described as bounds on both control amplitude and control rate of change. If the open loop system is unstable, such constraints limit the region of the state space where stabilization is possible. An application where this occurs is pitch axis control of modern aircraft. If there are two sets of control surfaces, the stabilization problem can be reduced to the form

$$\begin{aligned} \dot{x}_1 &= x_1 + x_2 + x_3 \\ \dot{x}_2 &= u_1 \\ \dot{x}_3 &= u_2 \end{aligned}$$

with upper and lower bounds on x_2, x_3, u_1 and u_2. If these bounds are all ± 1 the stabilizable region is shown in figure 5.1. The general theory behind the calculations is given in [61], [153].

5.3 Quantifier Elimination in Control

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

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

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 quantified variables (without u in the above case) which is equivalent

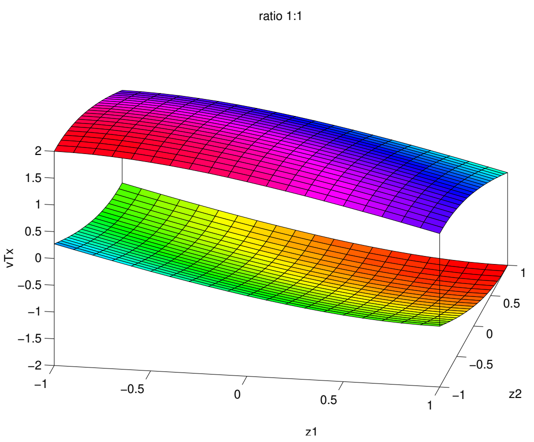


Figure 5.1: Stabilizable region of aircraft with two controls

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 was 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 most efficient implementations of QE-algorithms today are based on *Cylindrical Algebraic Decompositions*, (CAD). The method constructs a decomposition of $\mathbb{R}^n$ such that a given set of polynomials have constant sign on each component. Such a decomposition is a starting point for the elimination of quantified variables from a formula. An brief introduction to CAD is given in [110].

Questions regarding stability of SISO feedback systems with static nonlinearities can be formulated as QE problems. We have shown how to use the circle criterion and describing function method to compute sufficient conditions on parameters to ensure stability of the closed loop, see [67, 124]. Both parameters describing uncertainties, controller adjustment, and bounds on memoryless nonlinearities can be handled simultaneously.

The application of QE-methods in equilibrium calculations of nonlinear aircraft dynamics has been studied in [62, 85]. The set of possible stationary orientations of the aircraft w.r.t. the flight path (i.e. its angle of attack and sideslip angle) can be computed. The calculations also take constraints on control surface deflections (aileron, elevator, rudder) into account. The computations have been performed using the equations of motion for an F-16 aircraft. In Figure 5.2 the white region shows the possible combinations of angle of attack, α and sideslip angle, β (normalized scales). The problem of determine how fast a missile can turn have also been been treated using similar methods.

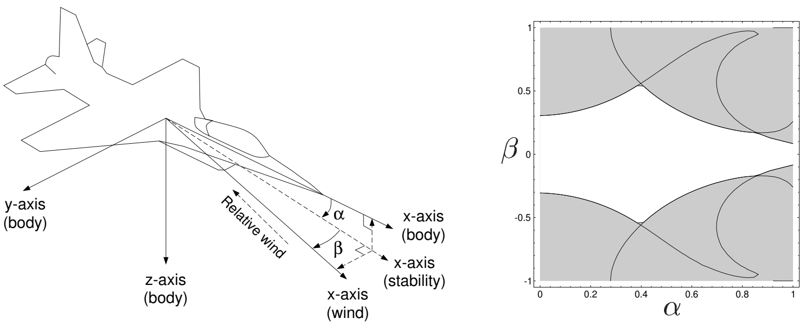


Figure 5.2: Aircraft orientation (α, β) and stationarizable orientations (white region) corresponding to admissible control surface deflections of an F-16.

In [79, 139] we consider a number of questions regarding dynamic systems described by polynomial differential equations subject to polynomial inequality constraints on the control signal. Which output levels correspond to asymptotically stable equilibrium points? Given a parametrized curve in the state space of the system. Is it possible to follow the curve by using admissible controls? A generalization of this is reachability computations along a family of curves, which also are studied.

A comprehensive treatment of the different topics in this section can be found in [7]. In this work the constructive approach to nonlinear systems analysis has been emphasized and a number of methods in computer algebra such as Gröbner bases, characteristic sets, and quantifier elimination are reviewed and utilized.

5.3.1 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 of structured singular values, or μ, which can be seen as an extension to H_∞ methods. These methods have attracted considerable interest since its

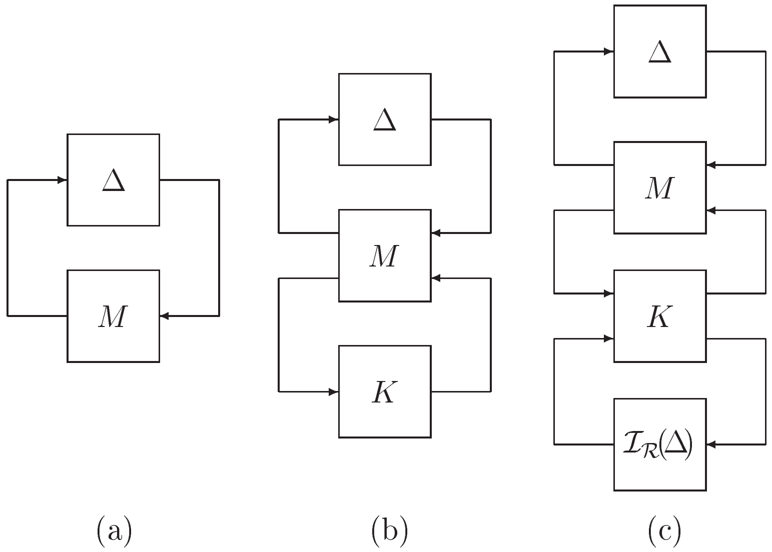


Figure 5.3: System with uncertainties. (a) The Δ block has a diagonal block structure, where each block may have different characteristics. (b) An uncertainty system with a controller K. (c) An uncertainty system with a gain scheduling controller. Here $\mathcal{I}_{\mathcal{R}}(\Delta)$ denotes a copy of some the uncertainties.

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 [44].

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 rate of variations is by using uncertainty augmentation [75].

The system is modeled as a system with feedback loops containing the parameter variations, uncertainties and perturbations, see Figure 5.3 (a). Using this formalism with are able to capture a quite general class of models. For instance nonlinear systems can in some cases be modeled as a linear system with nonlinear "uncertainty" elements in the feedback path. Also, performance bounds can be included similarly. Linear matrix inequalities (LMIs) can also be used to formulate an upper bound of the robustness measure.

The synthesis problem is depicted in Figure 5.3 (b). Here the objective is to find a controller K in order to tolerate as large uncertainties as possible without making the closed loop systems unstable. One approach to this problem is the so called D-K iterations. In [45] we present a design method based on passivity argument when also parametric uncertainties are present. This method is called Y-Z-K iterations. In [88] we present a method to fit rational matrix functions to frequency sampled data. This can be applied to D-K and Y-Y-K iterations with repeated uncertainty blocks.

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 5.3 (c). Previous synthesis results involving (complex) dynamic uncertainties have recently been extended to also include (real) parametric uncertainties [4, 41, 91].

An alternative and complement of using D-scalings in robustness analysis is to introduce parameter-dependent Lyapunov functions. Such Lyapunov functions can also be interpreted as parameter-dependent similarity scalings. This also alludes to a natural parametrization of such functions [4, 32, 75].

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 [43] that improves the approximation error compared to Hankel norm model reduction.

Chapter 6

Signal Processing

6.1 Navigation

Generally speaking, a navigation system is a system used for position and steering order determination. Typical tools today for navigation are *inertial navigation systems* (INS) and *global navigation satellite systems* (GNSS). The use of maps and terrain information (on charts or in databases) is of course also a major component. An integrated navigation system uses information from different sources in an efficient and reliable way to yield the best characteristics of the different subsystems. This also means that the navigation system should be capable of detecting faults and to adjust itself to the availability of certain types of information. An autonomous navigation system, i.e., a navigation system that does not depend on any sensors outside the vehicle, has an increased availability. Motivated by this the problems of fault detection in integrated navigation systems and autonomus navigation based on terrain elevation databases have been research topics.

This work has been performed within NUTEK competence center ISIS in cooperation with Saab Military Aircraft and Saab Dynamics AB.

6.1.1 Fault Detection in Integrated Navigation Systems

The ability to ensure the integrity of a navigation system, i.e., the ability of the system to detect and alert conditions when the navigation system output will place the vehicle outside a predetermined volume in space, is becoming increasingly important in aviation applications.

The use of multiple sensors and information sources in an integrated navigation system does not only yield a better navigation performance but also forms a good base for integrity monitoring using the analytical redundancy between the different information sources.

When multiple subsystems are involved one has the choice of performing integrity monitoring at different levels of the integration scheme. A multilevel monitoring scheme has been proposed [66], where the integrity monitoring takes place at each possible level, motivated by the fact that faults are detected faster closer to the source but that the overall solution still should be monitored for un-modeled faults.

The problem of integrity monitoring can be formulated as a change detection problem and the use of the Generalized Likelihood Ratio (GLR) test for integrity monitoring of integrated inertial/satellite navigation systems has been studied. The result was presented at the 9th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS-96) [84].

6.1.2 Navigation Using Terrain Elevation Databases

Consider the problem of aircraft navigation utilizing terrain information, presented in Figure 6.1. A radar altimeter measures the aircraft's ground

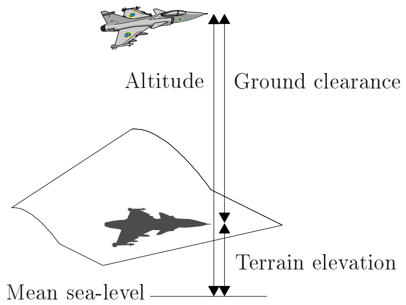


Figure 6.1: Terrain aided navigation.

clearance and a barometric altimeter measures the altitude over mean sea-level. Their difference equals the terrain elevation. A database map with pre-measured values of the terrain elevation is carried on board the aircraft and used to filter out matching terrain elevation profiles, yielding a position estimate of the aircraft.

Due to the repetitive structure of the terrain, the problem is in its nature very nonlinear. Hence, the local linearization techniques often used in nonlinear filtering yield poor results in this application. Further, the need to merge different types of measurements is nontrivial and calls for an unconventional solution. In [144] a Bayesian approach to the problem is studied. The general Bayesian framework has the ability to track several position hypotheses in parallel and to merge the sensors together in a reliable way. The aircraft's dynamics and its relation to the measurements may be described by the model

$$\begin{aligned} \mathbf{x}_{t+1} &= g(\mathbf{x}_t, u_t) + \mathbf{v}_t \\ \mathbf{y}_t &= h(\mathbf{x}_t) + \mathbf{e}_t. \end{aligned}$$

The Bayesian recursive solution, to this model, consists of a measurement- and a time update of the probability density function of the aircraft position,

$$\begin{aligned} f_{\mathbf{x}_t|\mathcal{Y}^t}(x) &\propto f_{\mathbf{e}_t}(y_t - h(x))\, f_{\mathbf{x}_t|\mathcal{Y}^{t-1}}(x) \\ f_{\mathbf{x}_{t+1}|\mathcal{Y}^t}(x) &= \int_{-\infty}^{\infty} f_{\mathbf{x}_t|\mathcal{Y}^t}(s)\, f_{\mathbf{v}_t}(x - g(s, u_t))\; ds. \end{aligned}$$

The algorithm is impossible to implement as it stands. By quantizing the state space the integral above becomes a sum and truncating this sum over a finite area yield an implementable algorithm.

Figure 6.2 shows a simulation of the algorithm over a five by five kilometer map, starting with a flat prior.

Only the areas of the map with probability greater than 10^{-5} are plotted, the true position of the aircraft is indicated by a circle. The ability to track parallel positions hypotheses is obvious in the figure. Further, the rate of area reduction is high without loosing track of the true position of the aircraft.

6.2 Radio Power Control

In an urban area, the channels used for mobile telephony are subject to Rayleigh fading due to multipath wave spreading. This will result in variations of the quality of the signal (usually measured in C/I - Carrier signal power/Interference signal power) when the mobile moves. For a TDMA

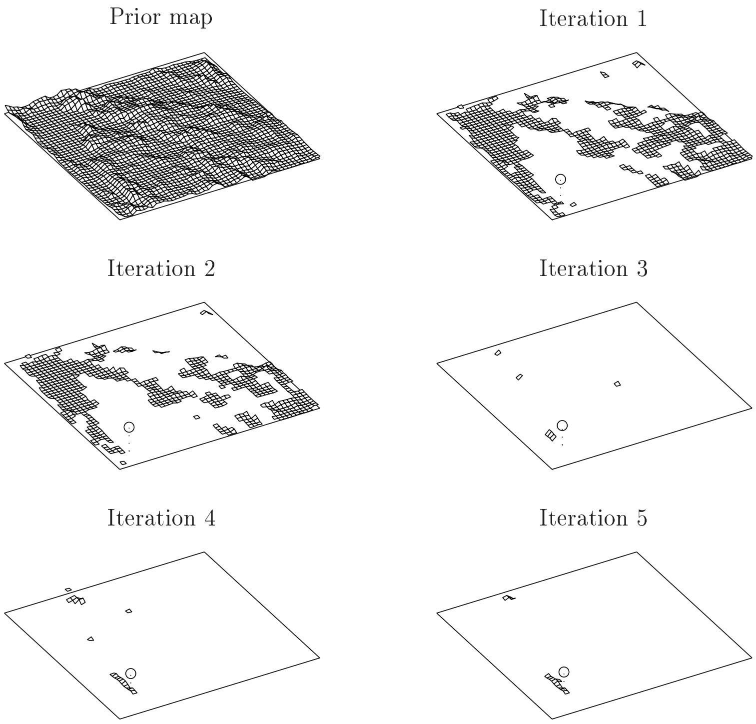


Figure 6.2: Areas with probability greater than 10^{-5}.

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 without this 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 studied in [6, 71] 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.

6.3 Friction Estimation in Cars

1992 a joint project between AB Volvo and Automatic Control, Linköping University was initiated for estimating the friction between tire and road in vehicles. 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.

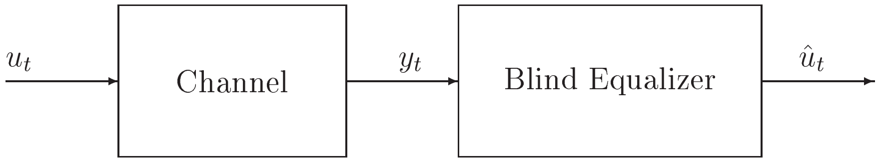
An overview of the work was presented in [48] and an article is now accepted for publication in Automatica. A change detection study was presented in [97] and an article version was submitted to *IEEE Control Systems*.

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.

6.4 Signal Processing in Communication

6.4.1 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* [19] 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.

In collaboration with David Huang at Brisbane University, some further aspects on identifiability are presented in a paper submitted to *IEEE Transactions on Communications*. Here sufficient conditions for identifiabiity are expressed in the terms of the output (instead of the unobservable input).

6.4.2 Echo Detection

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, but the problem is that the large number of inactive parameters only contribute to the variance error of the model.

This problem has been studied in collaboration with John Homer at Brisbane University, Iven Mareels and Bob Bitmead at Australian National University and Bo Wahlberg at KTH.

Besides this work, the mathematical problem posed above – which is also relevant for certain system identification problems, was studied in [78]. The idea is to estimate the active coefficients with Akaike-like criteria. A straightforward implementation consists in estimating all 2^d possible combinations of acitve taps, estimate them with RLS and then choose the combination that minimizes a loss function plus a penalty term. The suggested algorithm basically does this by applying one LMS filter to all coefficients and then compare them to a certain pre-computable threshold. This contribution was awarded the *IFAC Congress Best Poster Paper Prize, 1996*.

6.4.3 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 [63]. 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.

6.5 Change Detection

6.5.1 Detection of Abrupt State Changes

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* [21] 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.

6.5.2 Asymptotic analysis

In [48] asymptotic performance of a number of change detectors is analysed in terms of the power function. That is, the design parameters are assumed to be tuned to give a pre-specified confidence level (or false alarm rate) and the asymptotic power function (or delay for detection) is derived. The analysis is asymptotic both in the number of data and model order or a linear regression model, and it is not assumed that the true system or signal can be described within the considered model structures. It is shown that under-modelling in many cases is likely to benefit the power of the change detector. This was illustrated in a simulation study were the theoretical power suggests an optimal model order (less than for the true signal) which coincides with the one obtained by Monte Carlo simulations.

6.6 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] 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 $Y_{fb} - Y_{bf}$.

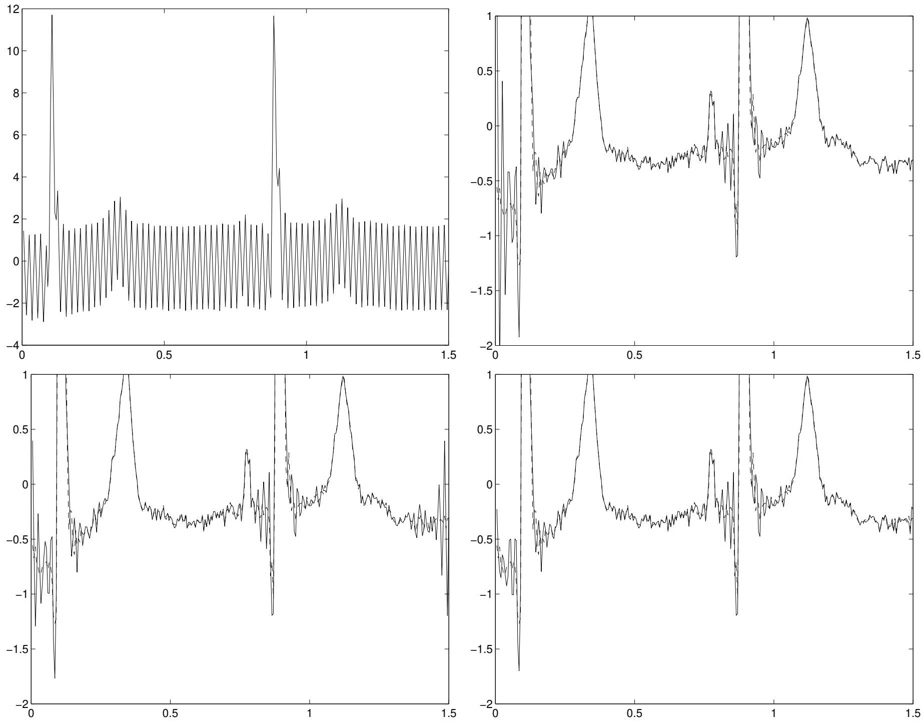


Figure 6.3: An EKG signal with a 50 Hz disturbance (upper left). The signal is filtered through a zero-phase Butterworth filter using Matlab's `filtfilt` (upper right), partial fractions (lower left) and finally using the new method (lower right). Dashed curve shows the true signal in the last three plots.

As an illustration, the first plot in Figure 6.3 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.

6.7 Target Tracking

6.7.1 Coordinate System for Extended Kalman Filters

A standard approach to tracking is to use the Extended Kalman Filter (EKF) applied to a non-linear state-space model. In [92] two conceivable choices of state variables for modeling civil aircrafts are compared. One where Cartesian velocities are used $(x_1, x_2, v_1, v_2, \omega)^T$ and one where absolute velocity and heading angle are used $(x_1, x_2, v, h, \omega)^T$. In both choices, Cartesian coordinates are used for position and angular velocity for turning. The choice of angular velocity ω as one state is motivated by that civil aircrafts usually do coordinated turns, which means that ω is piecewise constant, while the velocity change is very small. It is shown that the latter state vector always performs better. This is proven by considering the linearization error made in the Extended Kalman filter applied either to a time-continuous model or a discretized model. The result is supported by a Monte Carlo simulation study.

6.7.2 A Study on Multi-Model Approaches

The performance of target tracking can be considerably increased by using parallel filters. Each filter is matched to specific assumptions on the manoeuvres, and the relative probability of each assumption is computed. The problem here is the curse of dimensionality, the number of possible manueovre histories increases exponentially. There are two schools for limiting the number of hypothesis: merging and pruning. Merging has become very popular in the last ten years but in [58] we show that the performance of pruning is at least not worse.

Chapter 7

Hybrid and Discrete Systems

7.1 Physical Modeling and Simulation of Hybrid Systems

7.1.1 Physical Modeling

The reason why the term *physical modeling* has been coined is the need to distinguish between two extreme approaches to physical systems modeling. On the one extreme we have so called 'black-box modeling' where a mathematical model is fit to measurements. On the other extreme we have physical modeling 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 modeling activities, i.e. physical modeling or parameter estimation, may dominate the overall modeling effort. In this section we focus on the physical modeling process.

7.1.2 The General Approach

The classical engineering approach to physical (systems) modeling is best characterized as a three phase modeling paradigm. First, we have the *reticulation*, where the system is divided into, and described by, *physical mech-*

anisms and their interactions. The system is typically abstracted into a set of *idealized engineering concepts* such as resistance, capacitance, inertia etc. A network model consisting of interconnected physical mechanisms is then created. At this point, those properties of the observed system that are considered to be relevant to the purpose of the model are distinguished without going into mathematical details.

The second phase consists of a *mathematical characterization* where 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 both formal model analysis and simulation.

The bond graph formalism provides significant support in all three of these phases. In the system reticulation phase, bond graphs significantly support the modeling task by providing a small and well-defined set of primitive physical mechanisms. These elements are derived from first principles of energy conservation and they help the modeler making the potentially relevant aspects of the observed system explicit. 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 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 straightforward.

One of the features of bond graphs is that they allow the modeler 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 modeling, 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.

7.1.3 Hybrid Systems

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

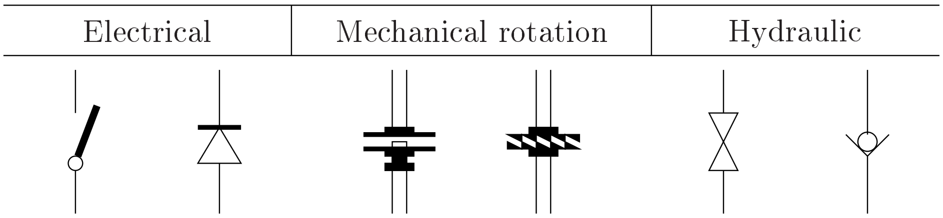


Figure 7.1: Some explicit discrete devices.

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

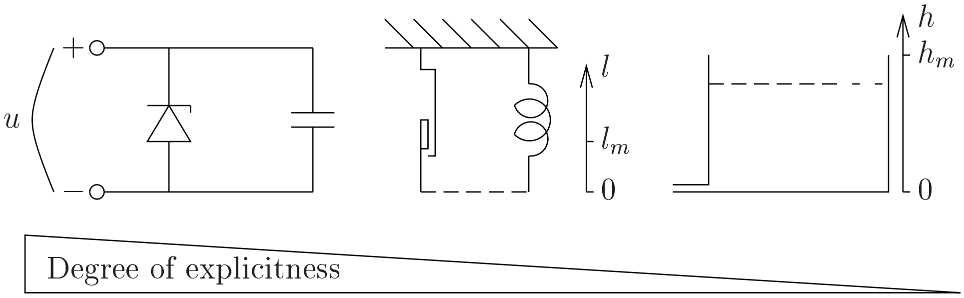


Figure 7.2: A spectrum of mode switching phenomena.

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*.

7.1.4 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 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, which is closer to the observed phenomena than the abstract mathematical description, assists in making explicit the relevant modeling 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.

For the purpose of representing discontinuous transitions a new candidate bond graph concept, the *ideal switch*, is used. The switch concept actually extends the modeling power of bond graphs, without any trade-offs in conceptual clarity, to mode switching systems as well. The achieved graphical

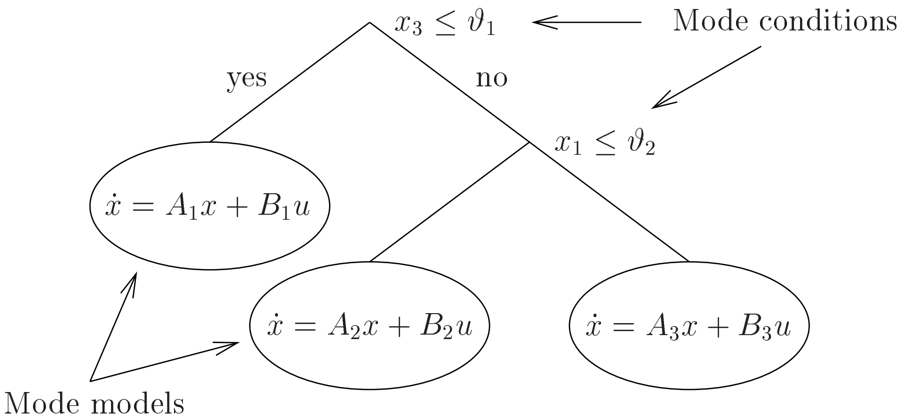


Figure 7.3: A model tree as a mode invariant representation.

model structure, the *switched bond graph* may be used for some graphical analysis, or to generate mathematical descriptions suited for simulation or formal analysis, as described in [65, 134, 8].

The **Sw**-element has two distinct *states*, namely *effort* ($\mathcal{E}$) and *flow* ($\mathcal{F}$) states. 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 to each other. Its state is however determined by a *control structure* $\Psi(\tau_e, \tau_f)$, which may be expressed in terms of a simple two-state transition system. Here the boolean transition conditions τ_e and τ_f denote any boolean (in-)equality relation between any of the continuous state variables in the model.

7.1.5 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 we reticulate the system as depicted in the schematic diagram in Figure 7.4 (right). Here the

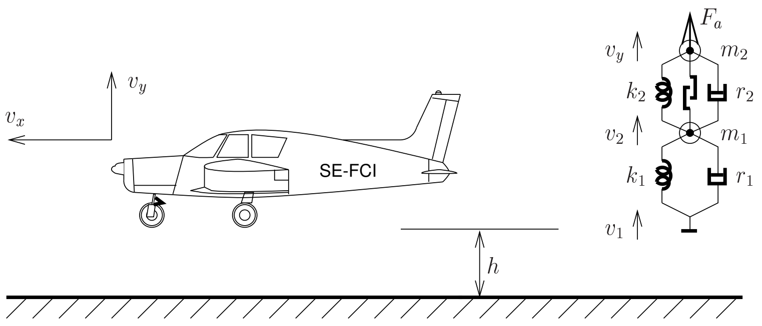


Figure 7.4: A hybrid system (left) and a reticulation of the same (right). m_1 is the mass of the wheel and damper sub-system and m_2 is the mass of the mainframe. F_a is the aerodynamic force acting on the mainframe.

damper r_1 and the spring k_1 represent 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 for switched bond graphs without any modification.

7.1.6 Equation Generation and Simulation

It is straightforward to generate a mathematical model from a switched bond graph. The procedure, described in [95, 135, 8], includes generation of a finite automaton describing the relations between the different modes as well as finding a continuous model for each mode. These continuous models can be derived using standard causality propagation and equation generation rules.

One benefit with the switched bond graph language is that the combinatorial explosion in the number of modes can be circumvented by deriving the description only for a few necessary modes. *MTS simulation* and *mode-by-mode simulation*, see [8, 149], are two extremes when performing simulation. In the first case the complete mathematical description of the model is derived before the numerical solution starts. In the latter case the derivation of simulation code and the numerical solution are nestled, in order to prevent deriving information that is not used.

To enable defining the interface between a switched bond graph simulation tool and a chosen numerical solver, a syntax for the derived description is

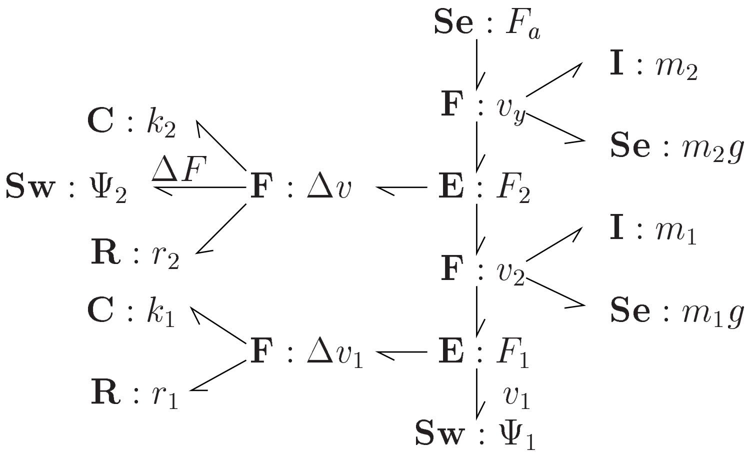


Figure 7.5: The acausal switched bond graph of the landing aircraft system.

presented in [8].

A mathematical description derived from the switched bond graph in Figure 7.5 is shown in Figure 7.6 and in Table 7.1. The modes are expressed using four state variables, where x_1 is the distance the spring k_2 is from equilibrium and x_2 the same distance for spring k_1. x_3 is the integral of the force acting on mass m_2 and x_4 the integral of the force acting on m_1. The transition conditions in the automaton are for each mode replaced by an expression in the state variables.

A primer to the modeling environment DYMOLA, with a simple mode switching system example, can be found in [111]

7.2 Discrete Systems

7.2.1 Introduction

In this section 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 the 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

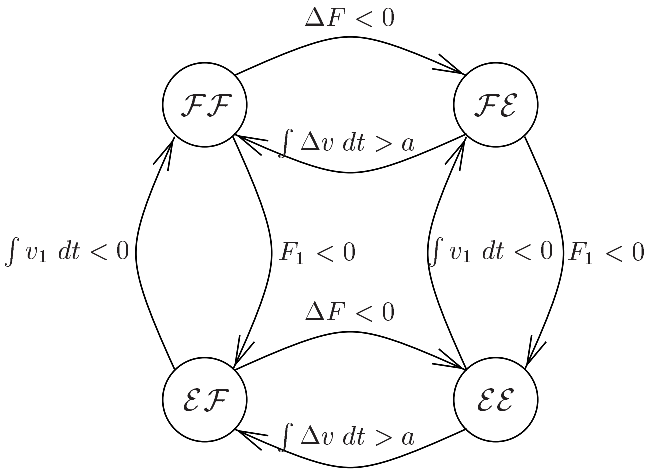


Figure 7.6: A finite automaton describing the relations between the different modes in the aircraft landing system example.

$\mathcal{FF}$	$\mathcal{FE}$
$\dot{x}_1 = 0$	$\dot{x}_1 = 0$
$\dot{x}_2 = \frac{1}{m_2}x_3$	$\dot{x}_2 = -\frac{k_1}{r_1}x_2$
$\dot{x}_3 = F_a - m_1 g - m_2 g - k_2 x_2 - \frac{r_1}{m_2}x_3 - \dot{x}_4$	$\dot{x}_3 = F_a - m_1 g - m_2 g - \dot{x}_4$
$x_4 = \frac{m_1}{m_2}x_3$	$x_4 = \frac{m_1}{m_2}x_3$
$\mathcal{EF}$	$\mathcal{EE}$
$\dot{x}_1 = \frac{1}{m_2}x_3 - \frac{1}{m_1}x_4$	$\dot{x}_1 = \frac{1}{m_2}x_3 - \frac{1}{m_1}x_4$
$\dot{x}_2 = \frac{1}{m_1}x_4$	$\dot{x}_2 = -\frac{k_1}{r_1}x_2$
$\dot{x}_3 = F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2}x_3 + \frac{r_2}{m_1}x_4$	$\dot{x}_3 = F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2}x_3 + \frac{r_2}{m_1}x_4$
$\dot{x}_4 = -m_1 g + k_2 x_1 - k_1 x_2 + \frac{r_2}{m_2}x_3 - \frac{r_1 + r_2}{m_1}x_4$	$\dot{x}_4 = -m_1 g + k_2 x_1 + \frac{r_2}{m_2}x_3 - \frac{r_2}{m_1}x_4$

Table 7.1: Equations for the four different modes in Figure 7.6.

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:

$$r(x(k), u(k), x(k+1)) \tag{7.1}$$

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 $f : X \times U \rightarrow X$ 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:

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

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.

7.2.2 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 [50, 86]. 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.

7.2.3 Polynomial Dynamical Systems over Finite Fields

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. For a tutorial see [81, 147].

Modeling

It is fairly complicated to use these polynomials directly as a modeling tool, see e.g. [83, 1, 146]. 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 [83, 94, 148, 83, 1, 145].

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 [1] and applied it to an industrial scale example [83] below.

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

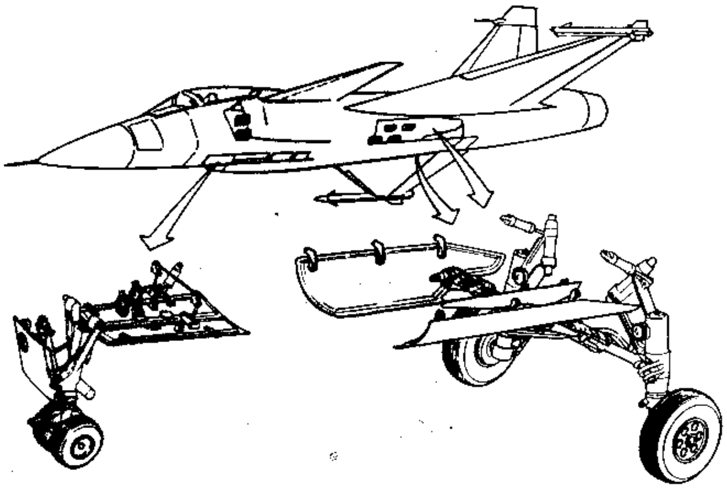


Figure 7.7: The landing gear system of the JAS 39 fighter aircraft.

or suggest any computational techniques for dealing with large systems[1]. We can readily use our efficient polynomial methods to carry out this design [1].

Another design framework, has been studied in [83, 1, 83]. 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.

7.2.4 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 7.2.3) applied to DEDS with industrial sized complexity: The landing gear controller (LGC) of the Swedish fighter aircraft JAS 39 Gripen. (See Figure 7.7.)

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

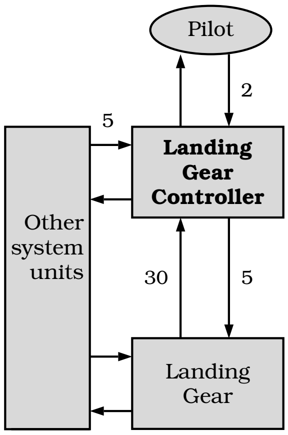


Figure 7.8: Controller interaction.

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 7.8.) 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 [83].

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

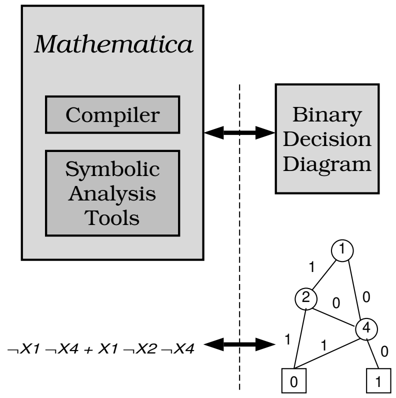


Figure 7.9: The symbolic tools used for the LGC.

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 7.9.

Modeling

Here we will focus on the modeling of the landing gear controller which corresponds to the upper part of Figure 7.10.

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 $0, 1, \dots, 15$ which makes it possible to represent each integer variable by four Boolean variables.

[2]Input, state and output variables.

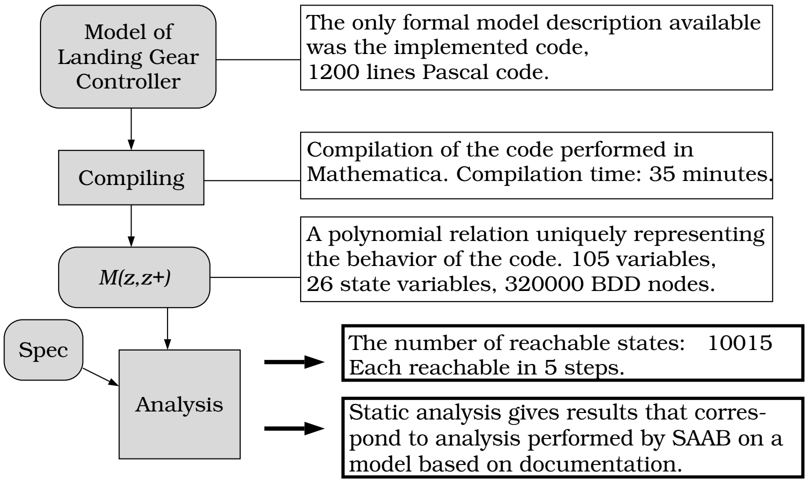


Figure 7.10: The modeling and analysis work performed on the LGC.

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:

$$\Phi : Pascal \times State \rightarrow State$$

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.

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

Suppose we have the Pascal expression

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

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

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

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.

Analysis

Here we will focus on the modeling of the landing gear controller which corresponds to the lower part of Figure 7.10.

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

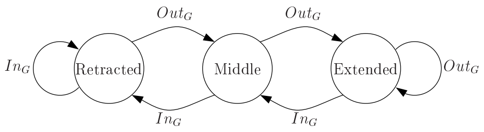


Figure 7.11: Model of the landing gears.

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.

Dynamic analysis is the performed on the restricted LGC model $\hat{M}(z, z^+)$ connected to a model of the plant, i.e. analysis of the closed loop behavior. The plant model is a simple 3-state automaton depicted in Figure 7.11 which encapsulates the discrete behavior of the real landing gear system.

The analysis proves if the closed loop behavior fulfills a formal specification represented by temporal logic expression such as

$$F_1(z) := \mathrm{EG}[\neg(Pilot(ext) \rightarrow Gear(ext))]. \tag{7.2}$$

which in turn represents the following sentence in natural language

> *The gear should always reach the extended state $Gear(ext)$ in finite time, when pilot command is extension $Pilot(ext)$.*

The verification captured 5 cases where 7.2 did not hold. By removing these cases by a less general (more detailed) specification and model the extension maneuver was proven to be correct. See [83] for further details.

7.2.5 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. In 1996 he was awarded an honorary doctor's degree from the Baltic State Technical University in S:t Petersburg, Russia and also received the Chester Carlson Prize.
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Anders Helmersson was born in 1957. In 1981, he received his M. Sc. in Applied Physics at Lund Institute of Technology. He has been with Saab Ericsson Space since 1984. In 1993 he joined the Control Group where he received his Ph.D in 1995. 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 1993and his Tekn.lic. in 1996 both 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 and his Tekn.lic. in 1996 both at Linköping University. His current research interest is in algebraic methods for nonlinear dynamic systems and verification of hybrid 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.
`email: magnusa@isy.liu.se`

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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Niclas Bergman was born in 1971. He received his M.Sc. degree in Applied Physics and Electrical Engineering from Linköping University in 1995. His current research interests are nonlinear Bayesian filtering, terrain-aided navigation and tracking.
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Anna Hagenblad was born in Lycksele, Sweden, in 1971. She received her M. Sc. degree in Applied Physics and Electrical Engineering in 1995 from Linköping University. Her current research interest is robust control of piecewise linear systems.
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Urban Forssell was born in 1970. He received his M.Sc. degree in Applied Physics and Electrical Engineering from Linköping University in 1995. His research interests include control-relevant identification and robust filtering.
email: ufo@isy.liu.se

Mikael Norrlöf was born in 1971. He received his M.Sc in Computer Science and Engineering 1996 at Linköping University. His current research area is robotic systems and he is doing his research in close cooperation with ABB Robotics in Västerås.
email: mino@isy.liu.se

Valur Einarsson was born in 1970. He received his B.Sc. in Mechanical Engineering in 1994 from the University of Iceland and his M.Sc. in Applied Physics and Electrical Engineering in 1996 from Linköping University. His current research interest is modeling and control of nonlinear systems.
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Per Spångéus was born in 1972. He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 from Linköping University. His current research interest is in the field of nonlinear systems.
`email: per@isy.liu.se`

Fredrik Gunnarsson was born in 1971 He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 from Linköping University. His current research interest is in the field of Radio Network Control.
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Jonas Blom was born in 1971. He recieved his M.Sc. in Engineering Physics in 1994 from the Royal Institute of Technology. His current research interest is in the field of Radio Network Control.
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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 was responsible for the computer network and the laboratory equipment. Since August 1996 he is employed by Scandicraft. `email: masun@scandicraft.se`

Mattias Olofsson, was born in 1970. He is employed as research engineer at the Division since July 1996, where he is responsible for the computer network and the laboratory equipment.
`email: mattiaso@isy.liu.se`

Ulla Salaneck is secretary for the control group.
`email: ulla@isy.liu.se`

Visitors

Professor Lei Guo, Academica Scinica in Beijing visited the Division as a guest researcher during October - December 1995.

Professor David Huang, Queensland University of Technology, Brisbane, Australia was visiting researcher at the Division during September - December 1995.

Morten Hanehøj, graduate student from University of Copenhagen, Danmark spent April - June 1996 at the Division.

Professor Daniel Rivera, Arizona State University, Tempe, AZ, USA, visited the Division during September - December 1996.

Corinne Ledoux, I.R.E.T.S., Arculeil, France visited the Department during September - December 1995

Appendix B

Courses

B.1 Undergraduate Courses

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

Since the activity report covers the second half of 1995 and the whole year 1996 some of the courses have been given twice during this period.

- *Automatic Control* (Reglerteknik) 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 and Engineering Biology (1996) Programs. 140+190 participants. Lecturer: Predrag Pucar (1995) and Tomas McKelvey (1996).

  Y Applied Physics and Electrical Engineering. 150 participants. Lecturer: Mille Millnert.

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

  Im Industrial Engineering and Management, Mechanical Engineering electives. 35+35 participants. Lecturer: Inger Klein.

  Ie Industrial Engineering and Management, Electrical Engineering electives. 90+80 participants. Lecturer: Torkel Glad (1995) and Inger Klein (1996).

- *Control Theory Y* (Reglerteori Y). 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. 110+80 participants. Lecturer: Lennart Ljung.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management Program. Multivariable systems, Sampled data systems, LQG-control. 35 Participants. Lecturer: Svante Gunnarsson.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Nonlinear systems, Signal processing. 20+25 participants. Lecturer: Svante Gunnarsson.

- *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. 150+90 participants. Lecturer: Mille Millnert (1995) and Fredrik Gustafsson (1996).

- *Modelling and Simulation* (Modellbygge och Simulering). For the Applied Physics and Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 90 participants. Lecturer: Torkel Glad.

- *Modelling of Industrial Systems* (Modellering av Industriella System). For the Computer Science and Engineering and Industrial Engineering and Management Programs. Physical system modelling, Bond Graphs, Identification, Simulation. 40+35 participants. Lecturer: Jan-Erik Strömberg (1995) and Inger Klein (1996).

- *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. 150 participants. Lecturer: Lars Nielsen

- *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, 25+15 Participants. Lecturer: Fredrik Gustafsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). For the Applied Physics and Electrical Engineering and Engineering Biology Programs. Interactive calculations, Programming, Graphics, Applications. 90 Participants. Lecturer: Fredrik Gustafsson.

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

- *Automatic control, EI* (Electrical Engineering) 5 units, 40+50 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.

- *Automatic control, advanced course, EI* 2 units, 40+40 participants. Contents: Sequential control and logic controllers. A typical industrial control system. Lecturer: Kent Hartman.

- *Automatic control, MI* (Mechanical Engineering) 4 units, 40+40 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

- *Nonlinear Systems*. Lecturer: Torkel Glad. Literature: Lecture notes.

- *System Identification*. Lecturer: Lennart Ljung. Literature: L. Ljung, System Identification. Theory for the User. Prentice Hall.

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

- *Modeling of Dynamical Systems*. Lecturer: Torkel Glad. A series of seminars by the participants.

- *Project in Engineering Systems Modeling*. Lecturer: Torkel Glad. Project oriented studies within ECSEL.

- *Robust multivariable control*. Lecturer: Anders Helmersson. Literature: K. Zhou, J.C. Doyle and K. Glover, Robust and Optimal Control. Prentice Hall.

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

Introduction to Convex Optimization with Engineering Applications. **Professor Stephen Boyd**, Electrical Engineering Department, Stanford University, Stanford, CA, USA. Short Course, August 23-25, 1995.

On Random Vibration Models. **Professor David Huang** Queensland University of Technology, Australia, September 21, 1995.

On Adaptive Control of Non-minimum Phase Linear Stochastic Systems. **Professor Lei Guo**, Academica Sinica, Beijing, China, October 12, 1995.

Testing if a Function Observed with Noise is Zero. **Professor Bernard Delyon**, Irisa, Rennes, France, November 23, 1995.

Modeling and Control of DC-to-DC Power Converters. **Professor Hebertt Sira-Ramirez**,Universidad de Los Andes, Merida, Venezuela, December 4, 1995.

Stability with Subspace Methods and MFD Toolbox ver 3. **Dr. Jan Maciejowski**, University of Cambridge, Cambridge, England, December 7, 1995.

The Use of Neural Network Hardware in Space, Physics and Engineering Sciences. **Dr. Thomas Lindblad**, Royal Institute of Technology, Stockholm, Sweden, January 11, 1996.

Some Issues in Paper Machine Control. **Dr. Krister Forsman**, ABB Corporate Research, Lund, Sweden, January 19, 1996.

Identification of nonlinear Wiener systems. **Corinne Ledoux**, INRETS, Université de Paris VI, Paris, France, January 26, 1996.

Initialization of the Prediction Error Calculations Used in System Identification. **Torben Knudsen**, Aalborg University, Aalborg, Denmark, February 8, 1996.

Real Time Data Bases for Telecommunications and Performance Polymorphism. **Peter Loborg**, IDA, Linköping University, February 15, 1996.

Real time data bases for telecommunications and performance polymorphism. **Thomas Padron-McCarthy**, EDSLAB, IDA, Linköping University, January 31, 1996.

Verification Automation in Software Development. **Dr. Staffan Bonnier** och **Tim Heyer**, IDA, Linköping University, February 29, 1996.

On Object Oriented Nondeterministic Supervisory Control. **Dr. Martin Fabian**, Chalmers Institute of Technology, Göteborg, Sweden February 29, 1996.

Friction Analysis based on Integral Quadratic Constraints. **Dr. Anders Rantzer**, Lund Institute of Technology, Lund, Sweden, March 18, 1996.

Nonparametric Statistical Techniques for Estimating Regression Functions. **Dr. Ola Hössjer**, Lund Institute of Technology, Lund, Sweden April 11, 1996.

Building Models of Robot-Camera Systems. **Morten Hanehøj**, Department of Computer Science, University of Copenhagen, Copenhagen, Denmark, April 18, 1996.

Efficient Nonparametric Identification and Adaptive Control for Minimum Variance Control Problem. **Dr. Alexander Nazin**, Institute of Control Sciences Russian Academy of Sciences, Moscow, Russia, April 23, 1996.

Linear and Nonlinear Design Trade-offs for Systems with Input Disturbances. **Dr. Stefan Graebe**, Profactor GmbH, Steyr, Austria, April 24, 1996.

Reduced Rank Linear Regression and Parameterization of Multivariable Linear Systems. **Professor Mats Viberg**, Chalmers Institute of Technology, Göteborg, Sweden, April 25, 1996.

Indexing Values of Time Sequences. **Ling Lin**, Department of Computer Science, Linköping University, Linköping, Sweden, April 25, 1996.

Signal Processing in the Ear and in Hearing Aids. **Johan Hellgren**, Linköping University, Faculty of Health Sciences, May 2, 1996.

Neural Networks and Soft Sensors. **Professor Heikki Koivo**, Helsinki University of Technology, Finland May 23, 1996.

An Information Theoretic Approach to Observe Path Design for Bearings-Only Tracking. **Dr Andrew Logothetis**, Dept of EE, University of Melbourne, Australia. June 13, 1996.

Mixed Quantitative and Qualitative Modeling: Means for Dealing with System Uncertainty. **Professor Francois E. Cellier**, University of Arizona, Tucson, AZ, USA, June 10, 1996.

Modeling, Analysis, and Control of Hybrid Systems. **Michael S. Branicky**, LIDS, MIT, Cambridge, MA, USA, June 14, 1996.

Presentation of activities at Chalmers University of Technology. **Anders Karlström**, Chalmers University of Technology, Göteborg, Sweden, September 9, 1996.

System Identification for Process Control Challenges. **Professor Daniel E. Rivera**, Arizona State University, Tempe AZ, USA, September 19, 1996.

Out of control? - Facing the complexity challenges in Embedded System Design . **Jonas Plantin**, Ericsson Radio Systems, Stockholm, Sweden, September 12, 1996.

Tuning of nonlinear controllers; ideas, insights and possibilities. **Dr. Jonas Sjöberg**, Chalmers University of Technology, Göteborg, Sweden, September 12, 1996.

Some Algorithmic problems in QFT. **Professor Per-Olof Gutman**, Technion, Haifa, Israel, September 18, 1996.

Control Synthesis for Batch Processes. **Dr. Michael Tittus**, Chalmers University of Technology, Göteborg, Sweden, October 3, 1996.

Short Course, Control Methods for the Process Industries. **Professor Daniel**

E. Rivera, Arizona State University, Tempe, AZ, USA, September 25, 1996.

On Roadway Control for Automated High System. **Dr. Alexander Stotsky**, S:t Petersburg State University, October 17, 1996.

Reconstruction of Noise Distorted Songs Signals. **Dalius Navakauskas**, Vilnius Technical University, Vilnius, Lithuania, October 31, 1996.

Some Guidance principles with Applications for Seeker Guided Missiles. **Dr. Henrik Jonson** Saab Dynamics AB, Linköping, Seweden, November 7, 1996.

Robustness Analysis of Uncertain and Nonlinear Systems **Ulf Jönsson**, Lund Institute of Technology, Lund, Sweden, November 14, 1996.

Adaptive Control of Systems with Nonlinear Parametrization. **Fredrik Skantze**, Motion Control Group ABB Robotics Products AB, December 12, 1996.

Active Databases for Monitoring and Control. **Martin Sköld**, Department of Computer Science, Linköping University, December 12, 1996.

A subjective look at modeling and identification. **James A. Sørlie** Lund Institute of Technology, Lund, Sweden. December 16, 1996.

Appendix E

Travel and Conferences

Lennart Ljung participated in the Second Russian-Swedish Control Conference in St Petersburg, Russia, August 28 - 31, 1995 and in the European Control Conference in Rome, Italy, September 4 - 8. He then took part in ICCoS Workshop on Future Directions on Identification, Vrije Universiteit Brussel, September 18 - 19. October 10 -12 he participated in ICANN'95 in Paris, France, where he also gave a tutorial at a Workshop in connection to ICANN'95. On October 16 -17 he took part in The MATLAB Conference in Cambridge, MA. On November 1 - 2 he participated in the MATLAB Conference, in Stockholm, and on November 13 he took part in a Seminar on the Occasion of IRISA's 20th birthday, IRISA, Rennes, France. He participated in the 34th CDC in New Orleans, LA, December 13 - 15, 1995, and February 1 - 3 1996 he visited ENSIED, Grenoble, France. June 2- 4 he partcipated in RVK'96 and , June 5 - 6 "Reglermöte'96"ec both in Luleå, Sweden. He participated in the IFAC World Congress in San Francisco, June 30 - July 5, 1996, and visited the Baltic State Technical University, in St Petersburg, Russia, October 2 - 4, 1996.

Torkel Glad participated in the Second Russian-Swedish Control Conference in St Petersburg, Russia, August 28 - 31, 1995 and in the European Control Conference in Rome, Italy, September 4 - 8 1995. He also took part in "Reglermöte'96", in Luleå, Sweden June 6 - 7 1996 and in the MTNS96 in St Louis, USA, June 24-28, 1996. Finally he participated in the 13th IFAC World Congress June 30 - July 5, 1996.

Håkan Fortell participated in the 2nd Russian-Swedish Control Conference in St Petersburg in August 1995, and in CDC'95 in New Orleans. LA, USA in December 1995.

Svante Gunnarsson participated in Reglermöte'96 in Luleå, Sweden and in the 35th IEEE Conference on Decision and Control, Kobe, Japan, December 11-13, 1996. He also has visisted the followig companies and institutions during 1995 - 96: Nynäs Petroleum, Nynäshamn, August 30 1995, KTH, Stockholm November 21, 1995, Scania AB, Södertälje, Februari 27, 1996, ABB Robotics, Västerås, March 29, August 16, November 22, NUTEK, June 12, 1996, Saab Dynamics, Jönköping, September 11, 1996 and Uppsala Univetsity, December 5, 1996

Kent Hartman participated in "Ingenjörsutbildningar i Norden" at Chalmers University of Technology, Göteborg, Sweden in June 1996.

Anders Helmersson participated in the third European Control Conference, Rome, Italy, September 5-8, 1995. He took part in Reglermöte-96, June 6-7, 1996. He attended the 13th World Conference of IFAC, San Francisco, California, June 30 - July 5, 1996. On December 11-13, 1996, he participated in the 35th IEEE conference on Decision and Control, Kobe, Japan. He was in a thesis jury on November 1, 1996 at Lund, Sweden.

Mats Jirstrand participated in "Reglermöte'96" in Luleå, Sweden, June 5 - 6, and in MTNS'96 in St Louis, Missouri, USA, June 24 - 28. He also attended the IFAC World Congress 1996 in San Francisco, California, USA, June 30 - July 5. He took part in the Second IMACS Conference on Applications of Computer Algebra, Linz, Austria, July 17 - 20 and the Fifth International Student Olympiad on Automatic Control in St Petersburg, Russia, October 2-4. On December 11 - 20 he visited the Information Systems Laboratory at Stanford University, California, USA.

Inger Klein attended the 14th International Joint Conference on Artificial Intelligence in Montreal, Canada, August 20-25, 1995. She participated in the 3rd European Workshop on AI Planning in Assisi, Italy, September 27-29, 1995, and attended DIMACS Workshop on Verification and Control of Hybrid Systems in New Brunnswick, New Jersey, USA, October 22-25, 1995.

Peter Lindskog attended the 5th ERNSI Workshop on System Identification in Cambridge, Great Britain, September.

Tomas McKelvey participated in the Russian Swedish Control Conference in St. Petersburg, Russia, August 31-September 2, 1995. In September 5-8 he took part of the European Control Conference in Rome, Italy. October 24 he visited the control group at Lund Institute of Technology. On November 23 he visited the signal, systems and control group at the Royal Institute of Technology. He attended the 34th IEEE CDC in New Orleans, Louisiana, December 13-15. June 6-7 he took part in Reglermöte'96 in Luleå, Sweden. June 10, 1996 he visited the department of mathematical statistics at Lund Institute of Technology. He attended the IFAC World Congress in San Francisco, July 1-5, 1996. He participated in the 5th ERNSI workshop on system identification in Cambridge, England, September 23-25, 1996. On December 11-13 he took part in the 35th IEEE CDC in Kobe Japan.

Jan Palmqvist participated in "GPS-seminarium" in Gävle, Sweden, March 20 1996. He took part in IEEE Position, Location and Navigation Symposium 1996 (PLANS'96) in Atlanta, Georgia, USA, April 22-26 1996. He also attended "Reglermöte'96" in Luleå, Sweden, June 6-7 1996. In September 17-20, 1996 he attended the 9th International Meeting of the Satellite Division of the Institute of Navigation (ION GPS-96) in Kansas City, Missouri, USA.

Anna Hagenblad, Niclas Bergman, Mikael Norrlöf participated in "Reglermöte'96", June 5 -6 in Luleå, Sweden,

Anders Stenman attended the "Reglermöte '96" in Luleå, Sweden, June 6–7 1996. He also took part in the 5th ERNSI Workshop on System Identification in Cambridge, England, September 23–25 1996, and the 5th International Student Olympiad on Automatic Control (BOAC '96) in St. Petersburg, Russia, October 2–4, 1996. He then participated in the 35th IEEE Conference on Desicion and Control in Kobe, Japan, December 11–13 1996.

Ulla Salaneck participated in "Rikssekreterarträffen" in Brussels, Belgium September 26 - 28, 1995, in "Reglermöte'96" in June, In Luleå, Sweden and in "Rikssekreterarträffen" in London, November 26 - 29, 1996.

Appendix F

Lectures by the Staff

Lennart Ljung: *Non-linear black box models in system identification* 2nd Russian-Swedish Control Conference, St Petersburg, August 29, 1995.

Lennart Ljung *System Identification through the eyes of model validation*, ECC, Rome, Italy, September 7, 1995.

Lennart Ljung: *Identification for control purposes*, ICCoS Workshop on Future Directions on Identification, Vrije Universiteit Brussel, Belgium, September 8, 1995.

Lennart Ljung: *Non-linear black box models in system identification*, Tutorial, Workshop at ICANN'95 (International Conference on Artificial Neural Networks), Paris, France, October 12, 1995.

Lennart Ljung: *Non-linear black box modeling in system identification.* ICANN'95, Paris, France, October 11, 1995.

Lennart Ljung: *What's new in the System Identification Toolbox, v4?*, The MATLAB Conference, Cambridge, MA, USA, October 18, 1995.

Lennart Ljung *System Identification and the System Identification Toolbox.* The MATLAB Conference, Stockholm, Sweden, October 31, 1995.

Lennart Ljung: *From Data to Model: A Guided Tour of System Identification*, Seminar on the Occasion of IRISA's 20th birthday, IRISA, Rennes, France. November 13, 1995.

Lennart Ljung: *Estimating the Total Model Error from Standard Model Validation Tests*. 34th CDC, New Orleans, LA, USA, December, 1995.

Lennart Ljung: *Properties of Closed Loop Identification* ENSIEG, Grenoble, France. February 1, 1996

Lennart Ljung: *A Personal View on How and Why Sub-space Methods Work* Uppsala University Workshop on Sub-space Methods. February 29, 1996

Lennart Ljung: *What is Possible to Control - the Principles of Automatic Control* The Royal Swedish Academy of Engineering Sciences, Stockholm May 9, 1996

Lennart Ljung: *Models - What do you have them for and how do you obtain them?* 25th Anniversary of the Systems Control Group, Uppsala University, Uppsala, Sweden. May 22, 1996

Lennart Ljung: *Models in Signal Processing* RVK'96 (Radiovetenskaplig Konferens) Luleå, Sweden, June 4, 1996

Lennart Ljung: *Hybrid and Discrete Systems in Control - Some (Linköping) Approaches* Reglermöte'96, Luleå, Sweden June 6, 1996

Lennart Ljung: *Estimating the Total Model Error from Standard Model Validation Tests* The IFAC World Congress, San Francisco. July 2, 1996

Lennart Ljung: *Development of System Identification* The IFAC World Congress, San Francisco. July 4, 1996

Lennart Ljung: *Hybrid and Discrete Systems in Control - Some (Linköping) Approaches* The Baltic State University, S:t Petersburg, Russia October 3, 1996

Lennart Ljung: *From Data to Model - A Guided Tour* The Royal Swedish Academy of Engineering Sciences, Stockholm, Sweden. In connection with the Chester Carlson Award. November 19, 1996.

Lennart Ljung; *Models - Thinking Aids in Complex Situations* The Tryggve Holm Lectures, Linköping University. December 4, 1996

Torkel Glad: *Ritt's algorithm in differential algebra* 2nd Russian-Swedish Control Conference, St Petersburg, August 1995.

Torkel Glad: *An algebraic approach to bang-bang control* ECC 95, Rome, Italy, September 8, 1995.

Torkel Glad: *Stabilizability under amplitude and derivative constraints (is Swedish)* Reglermöte 96, Luleå, Sweden, June 7, 1996.

Torkel Glad: *Stabilizability under actuator constraints: an application to aircraft control* MTNS96, St Louis, USA, June 24 1996

Torkel Glad: *Algorithms for differential algebra*, Universität Duisburg, Duisburg, Germany, October 30 1996.

Håkan Fortell: 2nd Russian-Swedish Control Conference, St Petersburg, August 1995.

Håkan Fortell: *A Generalized Normal Form and its Application to Sliding Mode Control* 34th CDC, New Orleans, LA, USA, December, 1995.

Håkan Fortell: *A Generalized Normal Form for Nonlinear Systems* Department of Automatic Control, Chalmers University of Technology, Göteborg, Sweden, February 2, 1996.

Svante Gunnarsson: *Evaluation of model quality in adaptive modelling* . Royal Institute of Technology, Stockholm, November 21, 1995.

Svante Gunnarsson: *Combining Tracking and Regularization in Recursive Least Squares Identification*, 35th IEEE Conference on Decision and Control, Kobe, Japan, December 12, 1996.

Mats Jirstrand: *Quantifier Elimination and Application in Control*, Swedish Control Conference, Luleå, Sweden, June 6, 1996.

Mats Jirstrand: *Computational Questions of Equilibrium Calculation with Application to Nonlinear Aircraft Dynamics*, The International Symposium on the Mathematical Theory of Networks and Systems, St.Louis, Missouri, USA, June 24, 1996.

Mats Jirstrand: *Nonlinear Control System Design by Quantifier Elimination*, IMACS Conference on Applications of Computer Algebra, Linz, Austria, July 19, 1996.

Mats Jirstrand: *Applications of Quantifier Elimination to Equilibrium Calcu-*

lations in Nonlinear Aircraft Dynamics, 5th International Student Olympiad on Automatic Control, St.Petersburg, Russia, October 2, 1996.

Mats Jirstrand: *Quantifier Elimination in Control Theory*, Information Systems Laboratory, Stanford University, California, USA, December 17, 1996.

Inger Klein: *Tractable Planning for an Assembly Line*, The 3rd European Workshop on AI Planning in Assisi, Italy, September 29, 1995.

Tomas McKelvey: *Frequency domain identification, subspace methods and periodic excitation*, 2nd Russian-Swedish Control Conference, St. Petersburg, Russia, August 31, 1995.

Tomas McKelvey: *System identification with periodic excitation signals: A subspace based algorithm*, Third European Control Conference, Rome, Italy, September 6, 1995.

Tomas McKelvey: *Model validation using geometric arguments*, Third European Control Conference, Rome, Italy, September 6, 1995.

Tomas McKelvey: *System identification from frequency data using subspace methods*, Lund Institute of Technology, Lund, Sweden, October 24, 1995.

Tomas McKelvey: *System identification from frequency data using subspace methods*, Royal Institute of Technology, Stockholm, Sweden, November 11, 1995.

Tomas McKelvey: *Asymptotic variance expressions for a frequency domain subspace based system identification algorithm*, 34th IEEE Conference on Decision and Control, New Orleans, Florida, December 13, 1995.

Tomas McKelvey: *Frequency weighted subspace based system identification in the frequency domain*, 34th IEEE Conference on Decision and Control, New Orleans, Florida, December 13, 1995.

Tomas McKelvey: *System identification using subspace methods*, Lund Institute of Technology, Lund, Sweden, June 10, 1996.

Tomas McKelvey: *System identification from frequency data using subspace methods*, Lund Institute of Technology, Lund, Sweden, June 10, 1996.

Tomas McKelvey: *Periodic excitation for identification of dynamic errors-*

in-variables systems operating in closed loop, IFAC World Congress, San Francisco, California, July 2, 1996.

Tomas McKelvey: *Parametrization of state-space models using tridiagonal matrix forms*, 5th ERNSI workshop, Cambridge, England, September 24, 1996.

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Appendix G

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Appendix I

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[162] P. Johansson. Target Tracking by fusing Radar and IR-sensor data. Master Thesis LiTH-ISY-EX-1607, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 951220.

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[170] C. Nilsson. Knowledge Based Specification of a Pilot Model for Complex Tasks. Master Thesis LiTH-ISY-EX-1673, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 951220.

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[172] M. Samuelsson. Investigation of a fast algorithm for electropmagnetic wave interaction on frequency-selective surfaces. Master Thesis LiTH-ISY-EX-1667, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 951219.

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[178] J. Bergmark. Adaptiv Friction-Compensation in Gun-Systems. Master Thesis LiTH-ISY-EX-1706, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960906.

[179] D. Bergquist. Signal processing of pedal information in an electrical control system. Master Thesis LiTH-ISY-EX-1652, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960403.

[180] M. Borgström. Modell order estimation for array antennas in noisy environments. Master Thesis LiTH-ISY-EX-1611, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960419.

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[189] E. Johansson. Integration methods for acceleration signals. Master Thesis LiTH-ISY-EX-1676, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960125.

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[191] J. Kansell. Suppression of harmonics in the line current for a four quadrant converter. Master Thesis LiTH-ISY-EX-1654, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960604.

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[199] H. Råström. Steel level control at continuous casting in a cast iron mould. Master Thesis LiTH-ISY-EX-1688, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960607.

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[202] M. Stern. Suggestion for an altitude meter for an autonomous miniature helicopter. Master Thesis LiTH-ISY-EX-1603, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960209.

[203] F. Svahn. Tools and Methods to Obtain a Passive Autofocus System. Master Thesis LiTH-ISY-EX-1715, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 961216.

[204] K. Wilhemsson. Recreation of engine sound in a driving simulator. Master Thesis LiTH-ISY-EX-1626, Dept of EE. Linköping University, S-581 83 Linköping, Sweden, 960229.

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