LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
1997

Contents

Chapter 1

Introduction

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

Our research interests are focused on the following areas:

- *Nonlinear 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 and diagnosis 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.

The Control Division takes active part in the NUTEK Competence Center ISIS (Information Systems for Industrial Control and Supervision), whose Director is Lennart Ljung.

The Control Division is also a central partner in the Research School ECSEL (Excellence Center for Computer Science and Systems Engineering in Linköping), which 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.

During the year Johan Gunnarsson defended his Ph.D. thesis, while six of our graduate students finished their Lic. Eng. degrees: Jan Palmqvist, Anders Stenman, Magnus Andersson, Urban Forssell, Magnus Larsson, and Niclas Bergman.

In the following pages the main research results obtained during 1997 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, most easily from our web-site.

We invite you to visit our home page:

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

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 FTP- or World Wide Web- services. This is our preferred method of distributing reports.

2.1 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`

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 (130.236.50.10)`

Or if you prefer to use you webbrowser for FTP:

`ftp://ftp.control.isy.liu.se/`

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.

Chapter 3

System Identification

3.1 Introduction

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

Several Tech. lic. theses were completed in the system identification area during the year. Anders Stenman, [3] describes the concept of Just-In-Time models, which is further treated in Section 3.7, while Urban Forssell defended a thesis on closed loop identification, [5]; see Section 3.3 for more details. Magnus Andersson treated estimation and experiment design problems for updating FEM-models of aircraft, see [4], and Section 3.4.

Some general expositions about the system identification problem include [46] for a basic overview, and [49] for software issues.

Some new results on recursive algorithms are given in [16] and [21]

3.2 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 [15] and [17], 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:

$$\left[\frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\tilde{G}(e^{i\omega})\right|^2\left|L(e^{i\omega})\right|^2|U_N(\omega)|^2\,d\omega\right]^{1/2}\leq$$
$$\leq\;(1+\eta)\left[\frac{1}{N}\tilde{\xi}_N^M\right]^{1/2}+(1+\eta)x_N+(2+\eta)C_u\sum_{k=M}^{\infty}|\rho_k| \qquad (3.1)$$

Here

- G_0 is a "true" description relating the input and output sequences by $y = G_0 u + v$, 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

$$\tilde{\xi}_N^M = \frac{1}{N}\left\|\sum_{t=1}^{N}\varphi(t)\varepsilon(t)\right\|_{R_N^{-1}}^2 \qquad (3.2)$$

with

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

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:

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

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

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.

Model validation issues were also the focus of the plenary presentation at the 1997 CDC in San Diego, [39].

3.3 Closed-loop Identification

In many practical situations identification experiments have to be carried out with the plant operating under output feedback, i.e., in closed loop. The reason might be that the system is unstable or that it has to be controlled for safety or economic reasons. We are then forced to use to closed-loop data for the identification. The problem is now that well known methods like instrumental variables, subspace methods, and spectral analysis all fail when applied directly to closed-loop data. On the other hand, a directly applied prediction error method will work fine and give consistent estimates of the open loop system given that the true system, including the noise properties, can be correctly modeled within the model class.

During 1997 we have studied various aspects of this problem which has resulted in a number of publications: [5, 39, 47, 50, 53, 58, 60, 69, 75, 79, 81, 82]. Most of the work has been focused on prediction error methods for closed-loop identification. The work reported in [5, 69, 82] has led to a unification of a number of different methods, both classical and more recent ones. These references contain both tutorial material and new analysis results for the statistical properties of the different methods. The variance properties of different closed-loop identification methods have also been studied in [75, 53]. A main result there was that the so called indirect methods give worse accuracy than the direct method. Here the asymptotic variance for the parameter estimates were compared. If we instead compare the asymptotic variance of the resulting transfer function estimates it can be seen that all methods give the same variance, given that the controller is linear [69, 50, 5].

In [79] we analyze the so called two-stage method, due to Van den Hof and Schrama. In this method the closed-loop sensitivity function is first identified and using this estimate a noise-free version of the input is simulated. This simulated input is then used for the identification of the open-loop system. If the first step was successful the resulting model will be consistent. However, it is often the case that the feedback controller contains non-linear elements such as anti-windup mechanisms and saturations. In such cases the two-stage method breaks down as it only considers linear models like FIR or ARX models in the first step of the algorithm. The main result in [79] (see also [5]) was that if one uses a non-causal model in the first step the method would still give consistent estimates regardless of the feedback mechanism.

Closed-loop identification has often been suggested as a means for dealing with unstable systems. Recall that in the prediction error identification the predictors have to be stable. With ARX and ARMAX models this is no problem since the unstable poles are shared between the dynamics model and noise model. However, if we would like to use output error or Box-Jenkins models this is not the case and these model structures cannot be used. To circumvent this researchers have proposed to use some indirect scheme in which first the stable closed-loop system is identified using an output error model and then the open-loop estimate is computed using some method. In [81] we show how to modify the output error and Box-Jenkins model structures to make them applicable also to the identification of unstable systems.

3.4 Experimental Design and 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. Model updating in general often suffers from undesired local minima in the cost function. In [4, 22] a novel cost function is introduced in order to reduce the risk of ending up in a local minima. In the proposed cost function the traditional technique of pairing modes was circumvented.

Locating actuators and sensors on a mechanical structure in order to measure its behavior form an important part of the experimental design. Classically this has been done manually using only engineering rules of thumb.

Most often it is impossible to analytically derive optimal sensor/actuator locations and one have to resort to numerical search schemes. In [4, 20] a model based sensor/actuator placement strategy is developed which also takes measurement noise into account.

3.5 Convergence Analysis

Asymptotic convergence analysis is a common and classical tool of assessing the properties of estimation and identification algorithms. The analysis determines what model an algorithm will identify when the number of data points tends to infinity and what statistical properties such an estimate will have. Common analysis tools are laws of large numbers and central limit theorems.

So called subspace methods for direct identification of linear state space models form a very useful alternative to maximum-likelihood type approaches, in that they are non-iterative and offer efficient numerical implementations. The algorithms consist of series of quite complex projections, and it is not so easy to intuitively understand how they work. The asymptotic analysis of them is also complicated. In [43] an interpretation of how they work in terms of k-step ahead predictors of carefully chosen orders is presented . It specifically deals how consistent estimates of the dynamics can be achieved, even though correct predictors are not used. This analysis gives some new angles of attack to the problem of asymptotic behavior of the subspace algorithms.

The maximum-likelihood estimation technique is a well known identification procedure for time domain data, i.e. when the identification data is samples of the time domain input and output signals. In [42] the multivariable frequency domain counterpart is derived and analyzed. In the frequency domain the identification data is samples of the Fourier transform of the input and output signals respectively. For a fixed noise model consistency of the estimator is established and analytical expressions for the asymptotic variance is derived.

Subspace based methods can also be applied to frequency domain data. In [44] we discuss how the time domain subspace based identification algorithms can be modified in order to be applicable when the primary measurements are given as samples of the Fourier transform of the input and output signals or alternatively samples of the transfer function. An instrumental variable (IV) based subspace algorithm is presented. Analysis show that this method is consistent if a certain rank constraint is satisfied and the frequency domain noise is zero mean with bounded covariances.

3.6 Parametrization Issues

System identification techniques based on optimization of some criterion function always implies that the model set, from within the optimal model is searched for, is parametrized in some fashion. In this section some approaches for selecting good parametrizations are presented.

Local Minimal Parametrization for State-Space Models

Many optimization problems involving the search over a set of linear systems cannot be formulated such that an analytical solution exists. Hence a nonlinear programming approach must be employed to find a local optimum in the parameter space. In [45] a minimal parametrization which is dynamically or adaptively changed during the optimization process is proposed. The basis is an over-parametrized model structure which can describe the set of all systems of given dimensions. However, at each step when performing the iterative optimization, we construct a local minimal parametrization. This reduces the search space to the minimal dimension. The construction of this local parametrization can be done efficiently and in such a way that the numerical operations in each optimization iteration becomes well conditioned. Particularly the condition number of the gradient matrix is of importance. In figure 3.1 the maximum condition number is presented for a range of simulated identification examples. The model order is increasing with the simulation number. In the figure the results of two different parametrizations are presented, the local parametrization based on the over-parametrized state-space model and a classical canonical parametrization. As model order increases the local parametrization clearly outperforms the canonical one. A high condition number of the gradient matrix often leads the optimization algorithm to a premature halt, far from the optimum.

Orthonormal bases for system identification

In the paper [14] we investigate the properties of a simple but very general construction for complete orthonormal bases for system identification. In the

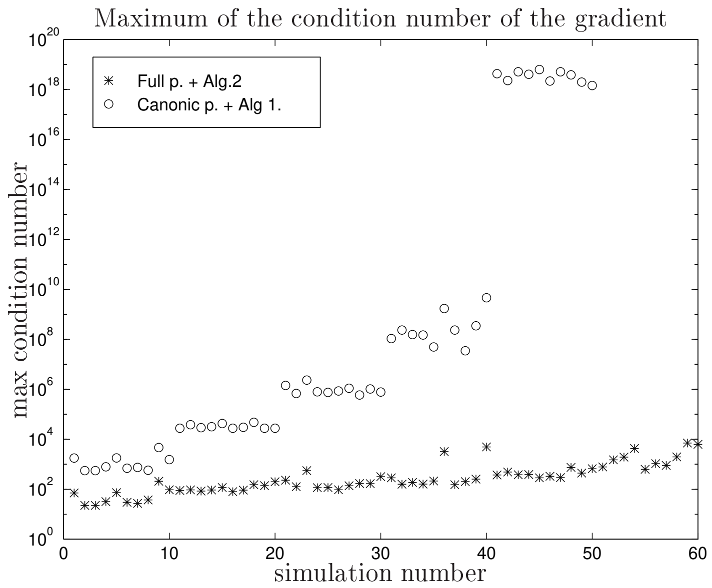


Figure 3.1: Results from Monte-Carlo simulations. Maximal value of the condition number of the gradient during the optimization.

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:

$$y(t) = \sum_{k=0}^{p} \left(\theta_k \mathcal{B}_k(q^{-1})\right) u(t) + e(t) \tag{3.3}$$

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.

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 wellknown result using blackbox 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 blackbox 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:

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

The complex conjugated poles are obtained from a spectral analysis showing four dominating oscillations. The left plot of Figure 3.2 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.

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 3.2 reflects the fact that by our choice of poles we aim at minimizing the bias error between 5 and 9 Hertz

[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

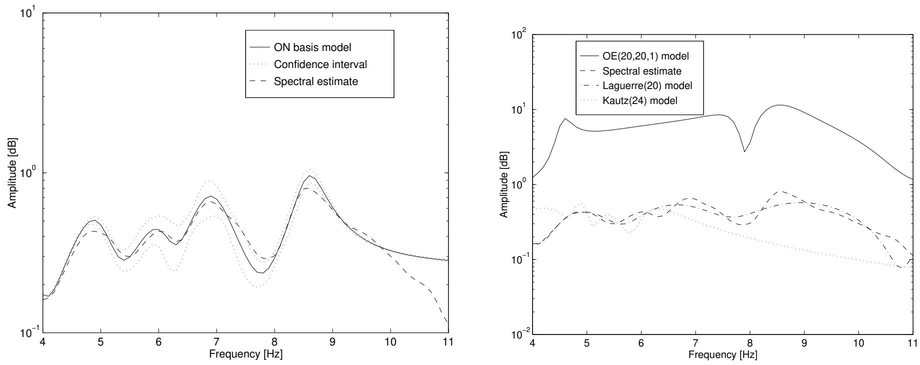


Figure 3.2: Transfer function estimate from non-parametric method and parametric model. Left: ON basis model structure with 12 parameters. Right: three standard model structures.

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.

Estimation of active parameters in large linear regressions

Some important practical signals and systems can be modeled by very large linear regression models where it is reasonable that most of the parameters are zero. In [34], we give an efficient method to solve this combined estimation and structure determination problem. It is related to Akaike-like criteria, and is based on one LMS filter and thus it is of low complexity. Asymptotic analysis shows that the method is consistent for finite impulse response models. A recursive algorithm is derived, which can be applied to time-varying systems as well. An example shows the efficiency of the approach.

As an illustration, consider the following FIR model of a communication channel subject to echoes:

$$y(t) = 6u(t-10) - 5u(t-51) - 1.5u(t-71) + e(t).$$

The input and measurement noise are independent Gaussian white noises. Figure 3.3 shows the result of the proposed algorithm averaged over 100 simulations. The correct taps were found in all simulations. The upper plot shows the estimated active taps. They converge quickly to the correct values 6, 5 and 1.5. Also the number of estimated active taps converges quickly to the correct number 3 as shown in the lower plot.

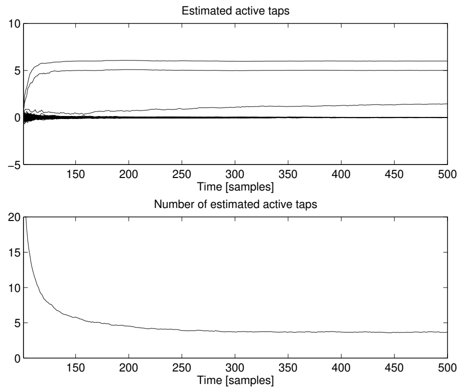


Figure 3.3: Estimated active taps (upper plot) and estimated number of active taps (lower plot)

3.7 Non-Linear Black Box Models

System Identification based on prior knowledge

By building structural and/or non-structural prior knowledge into model structures, one can in many practical situations obtain models that are "better" suited for their intended use. One natural 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).

In [23] we suggest 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 [10] it is emphasized that the most often used structure for *fuzzy identification* is a functional series expansion of the form

$$\hat{y}(t) = g(\varphi(t), \alpha, \beta, \gamma) = \sum_{j=1}^{n} \alpha_j \prod_{k=1}^{r} g_{j,k}(\varphi_k(t), \beta_{j,k}, \gamma_{j,k}), \tag{3.4}$$

where α, β, and γ 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. 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 [48] and [10] propose one particular fuzzy model structure parameterization that combines the richness and flexibility of (3.4) with such monotonicity features. This property, which is crucial to maintain for certain applications of the model, can be preserved through constrained estimation.

Just-in-Time Models

Traditional treatments of the nonlinear black-box modeling problem have usually involved *global* methods, such as neural nets, radial basis networks, wavelets or other nonlinear parametric models. However, when dealing with very large data sets, this approach becomes less attractive to deal with because of the complexity of the associated non-convex optimization problem.

Inspired by ideas both from local polynomial modeling and database systems technology, we have in [3] taken a conceptually different point of view.

We assume that all observations are stored in a database, and that models are built on demand as the actual need arises. When a model is really needed in a neighborhood of an operating point $\varphi(t)$, a subset of relevant data is retrieved from the database, and a local modeling operation is performed on that subset. For this concept, we have adopted the name *just-in-time models* (aka *model-on-demand*). The basic idea is to compute the fit *locally* within a "sliding window" $W_h(\cdot)$;

$$\hat{\theta}(\varphi(t)) = \arg\min_{\theta} \sum_{k=1}^{N} \ell(y(k) - g(\varphi(k), \theta)) \cdot W_h(\|\varphi(k) - \varphi(t)\|), \qquad (3.5)$$

where $g(\cdot, \cdot)$ denotes an arbritrary nonlinear mapping. Since we now have to solve an optimization problem for *each* prediction, the mapping is usually chosen such that it is linear in the parameters. Thus the local estimates can be obtained by simple and powerful least squares methods. However, the key issue here is how to select the weighting $W_h(\cdot)$. The standard solution, which has been extensively studied in the statistical literature, is to select the weights according to a *kernel function* parameterized by a parameter h (usually referred to as the *bandwidth*) which regulates the size of the neighborhood around $\varphi(t)$. Methods that use the available data to produce a good bandwidth are usually referred to as *bandwidth selectors.* They can roughly be divided into "classical" methods which are based on cross-validation ideas, and "plug-in" methods which rely on asymptotic MSE expressions. The majority of the bandwidth selectors proposed so far, though, have been of *global* type, i.e., they produce a single global bandwidth. However, adaptive (i.e., *local*) methods, which select local bandwidths for each prediction, have received a lot of attention in recent years, and the development of them still seems to be an open and active research area. In [3] we also study an optimization approach where the the weights are optimized so as to minimize certain performance measures. It is shown that this optimization can produce more accurate predictions for small neighborhood sizes. The asymptotic properties of the proposed optimization approach is discussed in [32].

In [3] we also extend the local modeling approach to the application of nonparametric *frequency response* estimation. Here the objective is obtain an estimate of a system's frequency function $G(e^{i\omega})$ by smoothing the ratio of the output's and input's Fourier transforms (the so-called ETFE). Classical solutions in this context are the Blackman-Tukey procedure which forms the estimate as a ratio between cross-spectra and spectra, and Welsh's method which forms the estimate as averaging of periodograms. A problem with these methods however, is that they use smoothing windows of fixed width and that this width has to be selected by the user using visual inspection. We show that better performance can be achieved by allowing a frequency dependent window width which adapts to the local properties of the ETFE. This is also concluded in [52].

Chapter 4

Non-Linear Systems

4.1 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 [38] systems of equations, inequations and strict inequalities are considered:

$$\begin{gathered} f_1 = 0, \dots, f_n = 0, \quad g_1 \neq 0, \dots, g_m \neq 0 \\ h_1 < 0, \dots, h_q < 0 \end{gathered} \tag{4.1}$$

The f_i, g_i and h_i are differential polynomials in some variables $y_1, \dots, y_N$, 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.

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 4.1 In many cases the stabilization is further complicated by the fact that some actuators are shared with the lateral control. A large manoeuvre in e.g. roll will therefore decrease the actuator range which is available for stabilization in pitch. An analysis of this situation, [37] results in a figure similar to 4.1, where the ratio of the distances between the surfaces at different corners gives a measure of the stabilization difficulties.

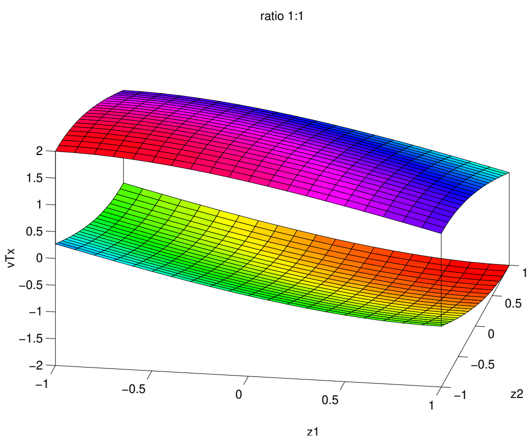


Figure 4.1: Stabilizable region of aircraft with two controls

4.2 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

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

This can be seen as a description of all points, $x \in \mathbb{R}^n$ of a nonlinear system, $\dot{x} = f(x,u)$ which can be made stationary by use of some admissible control, $u^2 \leq 1$.

The problem of *Quantifier Elimination*, (QE) consists of finding a formula without quantified variables (without u in the above case) which is equivalent 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.

The application of QE-methods in equilibrium calculations of nonlinear aircraft dynamics has been studied in [83]. 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 4.2 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.

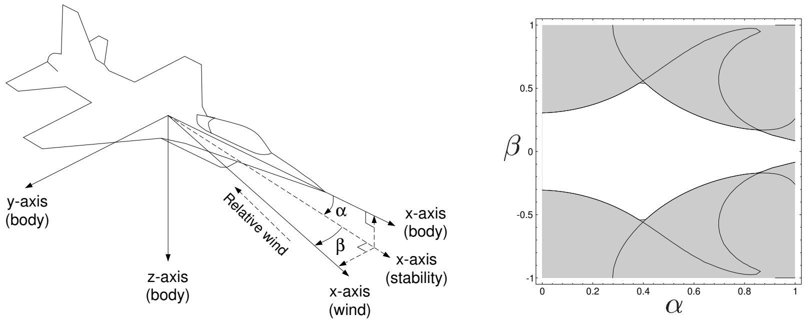


Figure 4.2: Aircraft orientation (α, β) and stationarizable orientations (white region) corresponding to admissible control surface deflections of an F-16.

In [29] 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 parameterized 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 [11]. 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.

4.3 Equilibria

Equilibria of a nonlinear system

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

are given by the equation

$$f(x, u) = 0 \tag{4.2}$$

The solutions form a set in x-u-space. In many applications one wants to move between different equilibria. The possibility of doing this is investigated in [84]. It is shown that it is possible to move between equilibria that can be connected by a curve of exponentially stabilizable equilibria. Moreover the transfer can be accomplished by staying arbitrarily close to equilibrium. In more complicated situations it might be necessary to switch control discontinuously because the set of equilibria is not connected. Such a case is shown in figure 4.3. The system dynamics is given by

$$\dot{x} = (u^2 + 4u - x + 3)(u^2 - 4u + x + 3)(x - u). \tag{4.3}$$

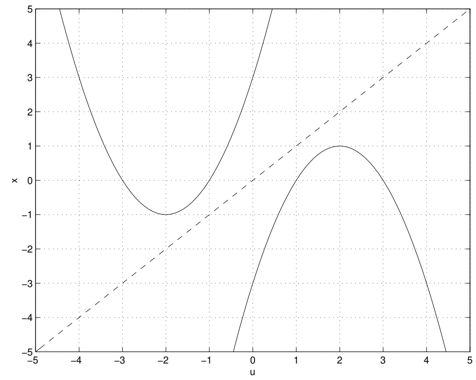


Figure 4.3: Equilibrium points of (4.3). Solid lines: asymptotically stable linearizations, dashed lines: unstable linearizations.

4.4 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 their introduction in 1982. The μ analysis can be seen as a refinement of the small gain theorem.

We can include knowledge about the structure of the 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. There is also an approach based on IQC methods which is described in [76].

The system is modeled as a system with feedback loops containing the parameter variations, uncertainties and perturbations, see Figure 4.4 (a). Using this formalism we are able to capture a quite general class of models. For instance nonlinear systems can in some cases be modeled as 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 4.4 (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 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 4.4 (c).

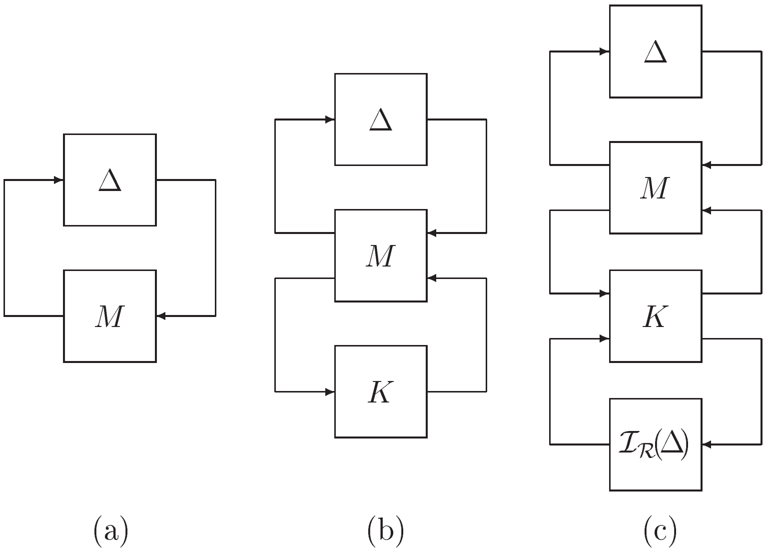


Figure 4.4: System with uncertainties. (a) The Δ block has a diagonal block structure, where each block may have different characteristics. (b) An uncertainty system with a controller K. (c) An uncertainty system with a gain scheduling controller. Here $\mathcal{I}_{\mathcal{R}}(\Delta)$ denotes a copy of some the uncertainties.

Scalings play an important role in robustness analysis. "μ-Synthesis with matrix valued scalings is discussed in [41].

Chapter 5

Signal Processing

The group's activity in the signal processing field is reported in this chapter. Main events of the year are the licentiate theses [2] and [7], both about navigation systems.

5.1 Fault Detection in Integrated Navigation Systems

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.

The ability to ensure the integrity of a navigation system, *i.e.*, the ability of the system do 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, 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 reported in [2] and [36].

5.2 Navigation Using Terrain Elevation Databases

Consider the problem of aircraft navigation utilizing terrain information, presented in Figure 5.1. A radar altimeter measures the aircrafts ground

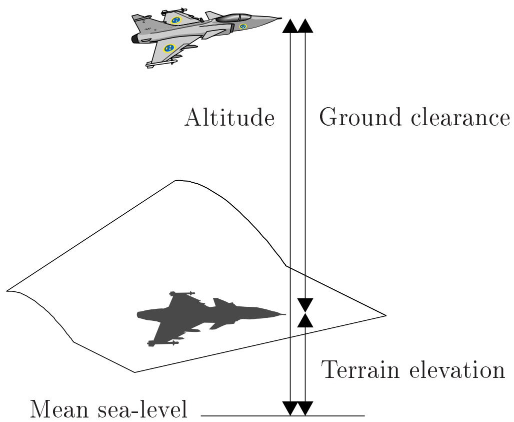


Figure 5.1: Terrain aided navigation.

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.

The problem admits a nonlinear state space model

$$\begin{aligned} x_{t+1} &= x_t + u_t + v_t \\ y_t &= h(x_t) + e_t \end{aligned}$$

where x_t is the two dimensional position of the aircraft in the map, u_t is the estimated movement of the aircraft obtained from an inertial navigation system, y_t is the measured terrain elevation, $h(\cdot)$ is the terrain map and v_t and e_t are noises acting on the system. The unstructured information in the terrain make the problem very hard to solve using standard algorithms for state estimation. The general Bayesian solution to the estimation problem consists of recursively updating the conditional filter density $p(x_t \mid Y_t)$. With some independence assumptions on the noises, the filter density obeys the recursion

$$\begin{aligned} p(x_t \mid Y_t) &= c_t \, p_{e_t}(y_t - h(x_t)) p(x_t \mid Y_{t-1}) \\ p(x_{t+1} \mid Y_t) &= \int p_{v_t}(x_{t+1} - x_t - u_t) p(x_t \mid Y_t) \, dx_t \end{aligned}$$

where c_t is a normalization constant. Due to the nonlinear terrain there is no way the express the filter density analytically. A novel approach to the estimation problem, based on a discretization of this solution, has been developed. Extensive simulations using genuine terrain data has shown that the algorithm yields very high performance over all types of terrain, the results have been reported in [18].

Since approximative solutions are inevitable in the application fundamental lower bounds on the performance of the algorithm has been derived and compared with the implementation using extensive simulations. It is shown in [71, 19] that the algorithm will reach the bound when the discretization distance is chosen small enough.

The results obtained in this terrain navigation project are reported in detail in the licentiate thesis [7].

5.3 Adaptive Filtering

Using MDL to Design Adaptive Filters

The minimum description length (MDL) has for some decades been known to be an efficient tool for choosing model structure. In [35], MDL is generalized to adaptive algorithms in system and signal identification. The parameter vector in these problems can either be considered as piecewise constant using segmentation and change detection algorithms or as time-varying estimated by recursive identification algorithms. MDL is derived as a measure of code length needed to transmit or store a signal. With the generalization we can compute not only the best model structure for the signal, but also when it pays off to use recursive identification and transmit the parameter updates together with the residuals, or if it is better to segment the signal and transmit the change points and the parameters. The approach opens an auto-tuning possibility, where the design parameters in the recursive identification and change detection methods can be optimized with respect to the code length.

Adaptive Estimation of Active Parameters

An adaptive filter dedicated to detect active parameters and thus to reject parameters in the model that are 0, is a by-product of the result described in Section 3.6.

Time-Frequency Resolution Using the Kalman Filter

The problem to track time-varying properties of a signal is studied in [13]. The somewhat contradictory notion of "time-varying spectrum" and how to estimate the "current" spectrum in an on-line fashion is discussed. The traditional concepts and relations between time and frequency resolution are crucial for this problem. We introduce two definitions for the *time resolution* of filters, essentially measuring the effective number of past data that are used to form the estimate. In, for example, wavelet transform techniques frequency dependent time resolutions are used so that fewer data are used at higher frequencies, thus enabling faster tracking of high frequency components (at the price of worse frequency resolution). The main contribution of the project is to show how this same feature can be introduced when estimating spectra via a time-varying, autoregressive model of the signal. This is achieved by a special choice of nominal covariance matrix for the underlying parameter changes.

As an illustration, an AR(4) model is simulated with four abrupt changes. The first two changes affect only the low frequency behavior, and similarly the last two changes affect the high frequency behavior. A frequency selective Kalman filter for a fourth order AR model is designed to track high frequency changes faster than low frequency changes. Its performance is shown in Figure 5.2.

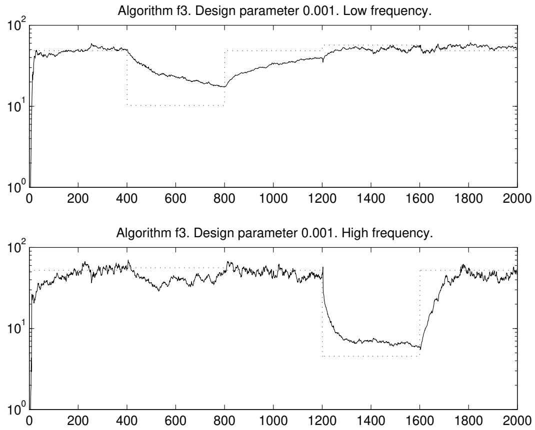


Figure 5.2: The spectral estimate $\hat{\Phi}_y(\omega, t)$ at two frequencies (upper plot:low, lower plot: high) using frequency selective KF

The performance is a parametric counterpart to the wavelet transform. One rationale to have different adaptation gains in different frequency bands is that intuitively a fixed number of periods of the frequency needs to be observed before getting statistical significance in the result. Thus, higher frequencies should be able to be tracked faster.

Chapter 6

Hybrid and Discrete Systems

6.1 Physical Modeling and Simulation of Hybrid Systems

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.

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 mechanisms* and their interactions.

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, that can be used for both formal model analysis and simulation.

The bond graph formalism provides support in all three of these phases. In the system reticulation phase, bond graphs support the modeling task by providing a small and well-defined set of primitive physical mechanisms.

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.

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.

By using the earlier introduces **Sw**-element, briefly reviewed in, e.g., [77], when making physical models using bond graphs, the support from bond graph formalism is extended to hybrid systems. Bond graphs including the **Sw**-element are referred to as switched bond graph.

Equation Generation and Simulation

It is straightforward to generate a mathematical model from a switched bond graph. The procedure 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. In addition some rules for initializing the continuous states in a mode have to be derived to complete the mathematical description. Since the states in most cases are continuous, the initialization is often trivial. In non-trivial cases the initial values can be found as solutions to equations generated from the bond graph [77].

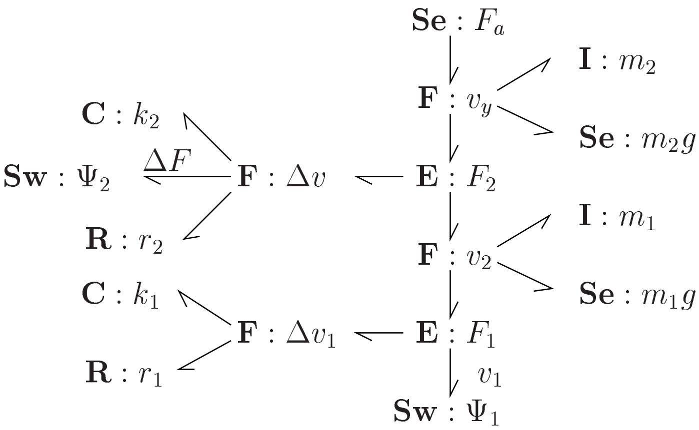


Figure 6.1: A switched bond graph model of a landing aircraft system.

A mathematical description derived from the switched bond graph in Figure 6.1 is shown in Figure 6.2 and in Table 6.1. The switched bond graph is a model of a landing aircraft system.

The continuous mode models are expressed using four state variables, where x_1 is the distance that the spring k_2 has from equilibrium and x_2 the same distance for spring k_1. x_3 is the momentum of mass m_2 and x_4 the momentum of m_1. The transition conditions in the automaton are, for each mode, replaced by an expression in the state variables.

In the landing aircraft system, all transitions but two have trivial initialization rules, and the equations for finding the initial values for the two transitions with non-trivial initializations, the ones where switch **Sw**:Ψ_2 changes to state $\mathcal{F}$, are found in Table 6.2. The first equation in the table states that the velocities of the two masses should be the same when the end-stop is reached, and the last equation describes the momentum conservation. The other two state variables are continuous.

When performing a simulation run it is not necessary to derive all equations at once. The most time efficient way to simulate is to derive equations when they are needed. When entering a mode, the initialization values of the mode are found, and the mode equations, together with the transition conditions for leaving the mode, are derived. Then the mode is simulated until a transition condition is met, whereafter equations for the new mode are derived.

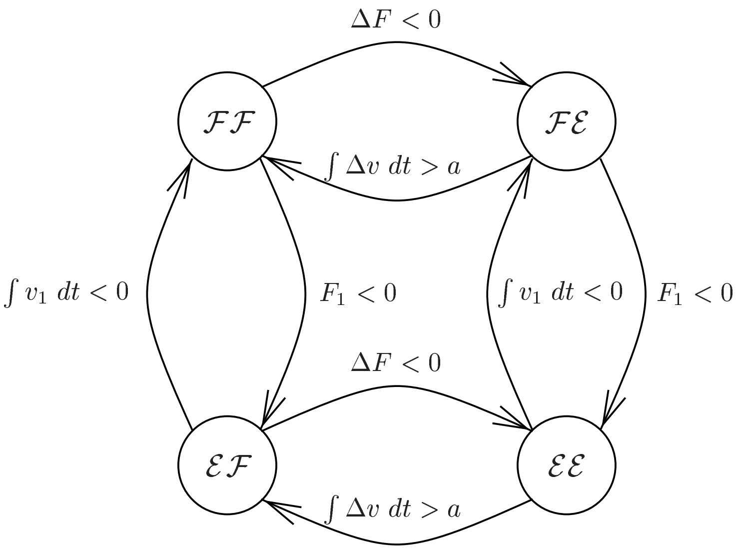


Figure 6.2: A finite automaton describing the relations between the different modes in the aircraft landing system example.

$\mathcal{FF}$

$$\begin{aligned}
\dot{x}_1 &= 0\\
\dot{x}_2 &= \frac{1}{m_2}x_3\\
\dot{x}_3 &= F_a - m_1 g - m_2 g - k_2 x_2 - \frac{r_1}{m_2}x_3 - \dot{x}_4\\
x_4 &= \frac{m_1}{m_2}x_3
\end{aligned}$$

$\mathcal{FE}$

$$\begin{aligned}
\dot{x}_1 &= 0\\
\dot{x}_2 &= -\frac{k_1}{r_1}x_2\\
\dot{x}_3 &= F_a - m_1 g - m_2 g - \dot{x}_4\\
x_4 &= \frac{m_1}{m_2}x_3
\end{aligned}$$

$\mathcal{EF}$

$$\begin{aligned}
\dot{x}_1 &= \frac{1}{m_2}x_3 - \frac{1}{m_1}x_4\\
\dot{x}_2 &= \frac{1}{m_1}x_4\\
\dot{x}_3 &= F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2}x_3 + \frac{r_2}{m_1}x_4\\
\dot{x}_4 &= -m_1 g + k_2 x_1 - k_1 x_2 + \frac{r_2}{m_2}x_3 - \frac{r_1 + r_2}{m_1}x_4
\end{aligned}$$

$\mathcal{EE}$

$$\begin{aligned}
\dot{x}_1 &= \frac{1}{m_2}x_3 - \frac{1}{m_1}x_4\\
\dot{x}_2 &= -\frac{k_1}{r_1}x_2\\
\dot{x}_3 &= F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2}x_3 + \frac{r_2}{m_1}x_4\\
\dot{x}_4 &= -m_1 g + k_2 x_1 + \frac{r_2}{m_2}x_3 - \frac{r_2}{m_1}x_4
\end{aligned}$$

Table 6.1: Equations for the four different modes in Figure 6.2.

$$\frac{x_4(t)}{m_1} - \frac{x_3(t)}{m_2} = 0$$
$$x_3(t) + x_4(t) = x_3(t') + x_4(t')$$

Table 6.2: Equations giving the initial values when switch $\mathbf{Sw}{:}\Psi_2$ changes to state $\mathcal{F}$. $x(t')$ is the value of state x before the change of mode, and $x(t)$ the initial value of x in the new mode. x_1 and x_2 are continuous.

An overview of switched bond graphs, and equation generation from switched bond graphs, can be found in [55].

6.2 Discrete Systems

Introduction

In this section we will present work on discrete event dynamic systems (DEDS) using a framework based on relations over finite domains. The framework is used for modeling, analysis, synthesis, and diagnosis of DEDS. One application is the dynamic verification of a large scale industrial application, the control code of the Swedish fighter aircraft, JAS 39 landing gear system. During this work many tools have been designed to better handle the complexity of problems and tasks present in industry today. The material presented here is based on the doctoral project[1] and covered in [40], and in the licentiate thesis [6].

A Relational Framework for DEDS

Our framework is based on finite domains. Subsets of some finite domain that represents a function or a relational entity will be called *relation sets*. The relational sets have in turn an abstract formal representation. These formal representations, that we call *relations*, are the formal tool that we use in our framework.

The reason for separating relations and relation sets are somewhat similar as for separating syntax and semantics. The syntax is the relation and the semantics is the relation set. We will use several different syntaxes for relations but the semantics (the relation sets) remains the same.

Example 6.2.1 Relation and Operators
Let $S_1 = \{0, 1, 2\}$ and $S_2 = \{3, 4\}$ be finite sets with integer elements. The *universe of discourse* (UoD) will be the cross product of S_1 and S_2 containing six elements.

$$\mathcal{U}_2 = S_1 \times S_2 = \{[0,3], [0,4], [1,3], [1,4], [2,3], [2,4]\}$$

Let $\mathcal{R}_1 = \{[0,4], [1,3]\}$ and $\mathcal{R}_2 = \{[1,3], [2,3]\}$. The corresponding relations will be written as

$$\begin{aligned} R_1(x_1, x_2) &= (x_1 == 0) \wedge (x_2 == 4) \vee (x_1 == 1) \wedge (x_2 == 3) \\ R_2(x_1, x_2) &= (x_1 == 1) \wedge (x_2 == 3) \vee (x_1 == 2) \wedge (x_2 == 3) \end{aligned}$$

Logic operations and set operations share the same axiomatic laws and can therefore be used in a similar way but for different domains.

$$R_1(x_1, x_2) \ \wedge \ R_2(x_1, x_2) = (x_1 == 1) \wedge (x_2 == 3)$$

$$\begin{aligned} R_1(x_1, x_2) \vee R_2(x_1, x_2) = {} & (x_1 == 0) \wedge (x_2 == 4) \vee \\ & (x_1 == 1) \wedge (x_2 == 3) \vee \\ & (x_1 == 2) \wedge (x_2 == 3) \end{aligned}$$

corresponding to $\mathcal{R}_1 \cap \mathcal{R}_2 = \{[1,3]\}$ and $\mathcal{R}_1 \cup \mathcal{R}_2 = \{[0,4], [1,3], [2,3]\}$.

The complement $\bar{\mathcal{R}}_1 = \{[0,3], [1,4], [2,3], [2,4]\}$ corresponds to negating the corresponding relation $R_1(x_1, x_2)$.

$$\begin{aligned} & \neg R_1(x_1, x_2) = \\ & \quad \neg\big((x_1 == 0) \wedge (x_2 == 4) \vee (x_1 == 1) \wedge (x_2 == 3)\big) = \qquad (6.1) \\ & \quad (x_1 == 0) \wedge (x_2 == 3) \vee (x_1 == 1) \wedge (x_2 == 4) \vee \\ & \qquad (x_1 == 2) \wedge (x_2 == 3) \vee (x_1 == 2) \wedge (x_2 == 4) \qquad (6.2) \end{aligned}$$

Note that it is not obvious at this point how to algebraically derive expression (6.2) from expression (6.1). In fact we have not yet decided the canonical form of relations. Canonical forms and algebraic manipulations will be discussed further in section 6.2. For now we just observe that (6.1) and (6.2) will have the same value (`true` or `false`) for the same values of x_1 and x_2. □

The example above presents a few of the logic operations that leads to algebraic manipulations of the relations, and that is used as the basic operations in our tools.

Concepts and Tools

A *relational model* $M(z, z^+)$ is a DEDS model where z is a collection of system variables and z^+ is a collection of variables representing the next value of z. $M(z, z^+)$ also includes a relation that represents some transition function describing the dynamics of the DEDS.

Example 6.2.2 State Space to $M(z, z^+)$
Consider a deterministic DEDS with inputs and outputs. This can be modeled by an explicit state space form such as

$$\begin{aligned} x^+ &= f(x, u) \\ y &= g(x, u) \end{aligned} \tag{6.3}$$

where f is the *transition function* and g is the *output function*.

An explicit state space form can be encapsulated into a relation model, by reformulating (6.3) into two equations which are then combined by an $\wedge$ -operator.

$$M(z, z^+) = (x^+ == f(x, u)) \wedge (y == g(x, u)) \tag{6.4}$$

where $z = \{x, y, u\}$. $\square$

Having $M(z, z^+)$ as the abstract representation of a DEDS, we formulate methods and tools for modeling, verification and synthesis that is based on the notion of relational models. Here we will only present a few of these; synchronous product and temporal logic verification.

Synchronous composition means that the transitions (or evaluations) of $M_1(z_1, z_1^+)$ and $M_2(z_2, z_2^+)$ are synchronous. The *synchronous product* ($\|$) of $M_1(z_1, z_1^+)$ and $M_2(z_2, z_2^+)$ is

$$M_1(z_1, z_1^+) \parallel M_2(z_2, z_2^+) = M_1(z_1, z_1^+) \wedge M_2(z_2, z_2^+)$$

In our framework we have used *temporal logic* (CTL) to formally represent a specification given in natural language. Temporal logic allows us to impose temporal conditions on the behavior, which means that we can have words like: *always, never, in future* and *after* in our behavioral specifications. See table 6.3 for a subset of temporal operators.

Example 6.2.3 Nonblocking
Let $m(z)$ be a relation for the *marked states* which can be regarded as final states after that some task is completed. A nonblocking system $M(z, z^+)$ is then a

Temporal Logic	Natural Language
$Q(z)$	$Q(z)$ holds in the initial state.
$\mathsf{EX}[Q(z)]$	$Q(z)$ can hold in the next time step.
$\mathsf{EU}[Q_1(z), Q_2(z)]$	$Q_1(z)$ will hold for finitely many steps and then $Q_2(z)$ can hold.
$\mathsf{EF}[Q(z)]$	$Q(z)$ can hold at some future time.
$\mathrm{EG}[Q(z)]$	$Q(z)$ can hold at all future times, i.e. from this point onwards.

Table 6.3: Temporal logic constructs.

system where the marked state set $m(z)$ is always reachable. This property can be expressed by using temporal logic.

A system $M(z, z^+)$ with marked states $m(z)$ is *nonblocking* iff

$$\mathsf{Verify}(M(z, z^+), \mathsf{EF}[m(z)]) = \mathtt{true} \tag{6.5}$$

□

Relational Representations

Relations and relational models are the abstract object we use in our framework. The way we choose to represent these relations in algorithms is dependent on what type of problems we are interested in. There are several way to represent relations in algorithms. If we use polynomials over *finite fields* we can use algebraic tools like Gröbner bases or graph based polynomial representations like the *Integer Monomial Diagrams* (IMD) [1]. Gröbner bases are not yet scalable to complex problems, and for the IMDs this is an open problem.

We will in this section briefly present *Integer Decision Diagrams* (IDD) [1] which is one of the representations we use. IDD has been introduced as an extension to *Binary Decision Diagram* (BDD), which is an efficient representation of relations of Boolean variables. The IDDs can represent function and relations including variables of the Boolean domain as well as for larger domains. The IDD have except for the logical operations also arithmetic operations like +,−,×, max etc. The IDD implementation [1] is done by incorporating the IDD in an efficient BDD-software.

Both BDD and IDD are reduced function graphs that are compact and provides a canonical form for Boolean and integer expressions respectively.

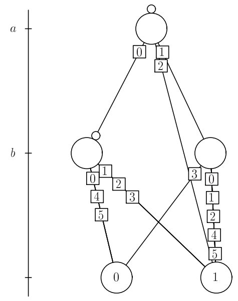


Figure 6.3: An example of an IDD.

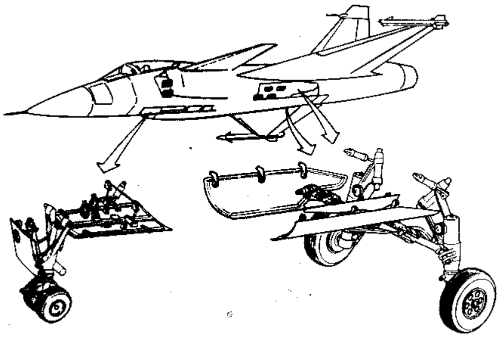


Figure 6.4: The fighter JAS 39 Gripen.

Example 6.2.4 IDD
Consider the two variables $a \in \mathbb{Z}_3$ and $b \in \mathbb{Z}_6$, and the relation

$$(b > 2a) \wedge (b < 4) \tag{6.6}$$

which is represented by the IDD in figure 6.3.

The complement edges[1] are showed as edges terminated by a ring. The root vertex is also complemented which means, e.g, that the edge corresponding to $a = 2$ should be interpreted as having the value 0 (`false`). □

Verification of Landing Gear Controller

We have modeled and analyzed an existing discrete subsystem of a modern fighter aircraft, the landing gear system on the Swedish fighter aircraft JAS 39 Gripen. See figure 6.4.

The purpose of the *landing gear controller* (LGC) is to perform maneuvers of the landing gears and the corresponding doors which enclose the gears in retracted position. The LGC 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. The state of the LGC is represented by 26 Boolean variables. The only formal description of the controller available to use was the actual implemented 1200 line Pascal code.

Modeling of the LGC

In the modeling part of the project the implemented Pascal code of the LGC was compiled to a relational model. The Pascal code is first parsed to a intermediate code called MPascal which essentially is the same Pascal code written as a *Mathematica* expression. This code is then processed by a compiler, also written in *Mathematica*. The result from the compiler is a polynomial model, denoted $C(z, z^+)$, represented as a BDD, where all static and dynamic relations between input variables and output variables are stored whereas temporary variables in the code are removed.

Closed Loop Verification

Having a polynomial model for the LGC, $C(z, z^+)$, we need a model for the plant, i.e., the physical landing gear. The sensors of the landing gear system determine if the gears are retracted, extended or in between. Therefore we use the three state automata in figure 6.5 as an illustration for the plant model $P(z, z^+)$. This model has two input signals In and Out that are controlled by the LGC when connected into closed loop. The input signal Man is an auxiliary signal for verification purpose. The plant model stays in the middle state until Man becomes `false`. The outputs in this model correspond to the sensors in the physical plant, but are not shown in figure 6.5.

[1] The small circles mark the logic complement $\neg$.

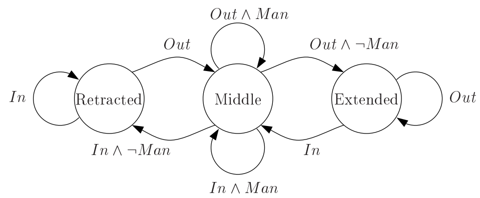


Figure 6.5: Landing gear model.

By connecting the LGC model, $C(z, z^+)$ and the plant model $P(z, z^+)$ we get the closed loop model

$$G(z, z^+) := C(z, z^+) \wedge P(z, z^+).$$

To verify the behavior of the closed loop model we use temporal logic to formally represent the specification of the behavior. If we want to verify the following specification: *"The gear should always reach the extended state $Gear(ext)$ in finite time, when pilot command is extension $Pilot(ext)$."* we can search if there exists behavior not fulfilling the statement above by using the temporal expression

$$F(z) := \mathrm{EG}[\neg(Pilot(ext) \rightarrow Gear(ext)) \wedge \neg Man].$$

By adding $\neg Man$ to the temporal expression we specify that the plant model will reach the extended state in arbitrary but finite time if the LGC command *Out* is `true` long enough. This shows that temporal logic can be powerful for modeling complex behavior in a compact way.

The verification is performed by tools developed by the authors in *Mathematica* as

$$S(z) := \texttt{BDDTLEvaluate[}G(z, z^+)\texttt{,}F(z)\texttt{]}.$$

The result is $S(z) \neq$ `false` which means that there exists behaviors where the specification above is not true. From $S(z)$ we can analyze why this is the case and build a more detailed specification, i.e., we get a more complete $F(z)$ from which the verification result was $S(z) =$ `false`, i.e., the correctness of the LGC was proved. We have also used more complex plant models where sensor errors are added to the behavior. The result of the verification proves that the behavior of the controller code is correct even for sensor failures of the plant.

The project has showed that it is possible to do dynamic analysis of complex systems (>100 boolean variables for $G(z, z^+)$) by using formal symbolic techniques.

Performance Improvements using IDDs

The software for this project was originally designed for BDDs. The experience of the BDDs in the project is that the representation of integers are rather cumbersome. This motivated us to implement the IDDs by rewriting the BDD package into an IDD package.

We have run all the computations of the landing gear project both with BDDs and IDDs to be able to compare performance. The main difference of course is that when we use the IDD we represent all integer variables in the Pascal code with only one IDD variable.

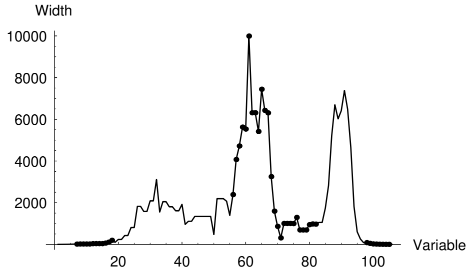
The total computation time for both compilation and verification is for BDD 35 minutes and for IDD 16 minutes on a 125MHz HyperSparc. The most time consuming part, as expected, is the compilation of the LGC. But we have to remark that during this compilation the BDD/IDD package has to rebuild the structure several times, i.e., new memory must be allocated and the unique and cache tables are rebuilt. A second compilation of the LGC would take perhaps 10% less time to compute.

We will also present some figures comparing the size (number of vertices) of the LGC relation represented by BDD and IDD respectively. Figure 6.6 shows the *width* of the LGC relation model represented as a BDD and as an IDD. The width of a BDD/IDD graph is the number of vertices for each variable included in the graph. In the figure we have also marked the variables corresponding to integer bits by a dot.

By integrating the widths of the BDD/IDD representation we get a meassure of the total amount of memory used. From that we see that the IDD representation is more smaller compared to the BDD representation.

6.3 Diagnosis

With the growing complexity of todays engineering systems, the need has arisen for systematic approaches to failure diagnosis. We have proposed an approach for modeling and diagnosis of systems that fall in the area of discrete event dynamic systems [6]. The approach is applicable to all systems



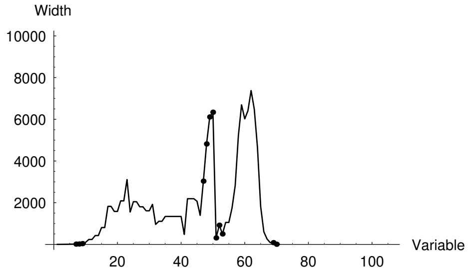


Figure 6.6: The width of the BDD (left) and the IDD (right) representing the LGC relation. The marked points correspond to integer variables.

that at some level of abstraction have an interesting discrete event dynamics that can display faulty behavior. The systems suitable for this approach typically consist of several interacting components where abrupt, but non-catastrophic, faults can occur in the components.

With the term diagnosis we mean fault detection and fault isolation, i.e., from observations of the system determine if a fault has occured, where it occured and what it is.

We use the relational framework for discrete event dynamic systems focusing on a conceptually simple representation of the relationships between inputs, outputs and states of a discrete event system as described above.

The diagnosis approach consists basically of three steps:

i) The construction of a discrete event model of the system to be diagnosed, containing both the normal and faulty behavior.

ii) Fault detection and fault isolation procedures using observations from the real system.

iii) Analysis of diagnosability properties of the system.

Modeling

Components are modeled locally in reusable component models including both normal and faulty behavior. Faults are modeled as unobservable inputs or states and represented with dedicated fault variables. The mapping from system variables to sensor readings is obtained globally and included in the relational model.

To illustrate the methods and concepts, we consider a very simple example system which is shown in figure 6.7 that consists of a valve, a pump, a sensor that indicates presence or absence of flow, and a controller. In the figure, the

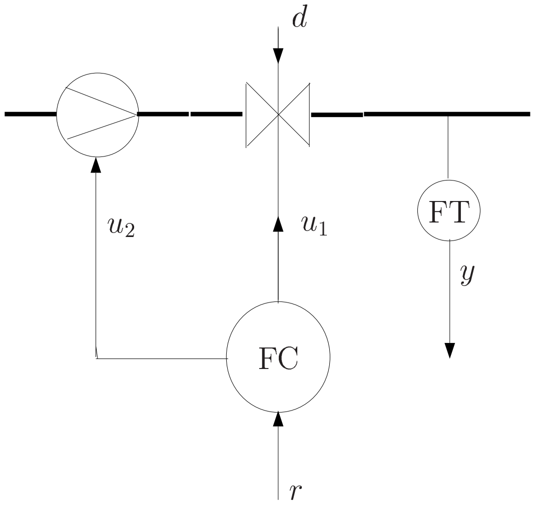


Figure 6.7: Flowchart of a simple system.

controller is denoted FC (Flow Control) and the sensor is denoted FT (Flow Transmission). The pump and the valve can be either on/off respectively open/closed. The valve can fail in two different ways, stuck open or stuck closed.

The fault that can occur in the valve will be modeled simply as an unknown input, d, that can take the values

$d = 0$	The valve is stuck closed.
$d = 1$	The valve is working, i.e., responding to u_1.
$d = 2$	The valve is stuck open.

The other variables indicated in Figure 6.7 will be Boolean valued, with the obvious interpretation. For example $u_1 =$ `true` means the valve is ordered open, etc.

For the controller, we have the FSM in Figure 6.8. The sensor measures if

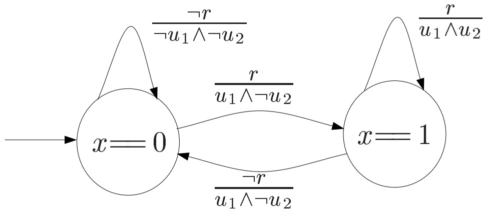


Figure 6.8: The controller.

there is flow in the pipe. The condition for the sensor output h to be `true` is that both the pump and the valve enables flow. This can be expressed as

$$y = \phi_V \wedge \phi_P$$

where

$$\begin{aligned} \phi_V(d, u_1) &= (d == 1 \wedge u_1) \vee (d == 2) \\ \phi_P(u_2) &= u_2 \end{aligned}$$

The sensor relation hence is

$$S(y, u_1, u_2, d) = (y == (\phi_V \wedge \phi_P))$$

The model of the system can then be obtained by

$$M(x, d, r, y, x^+) = \\ \exists u_1, u_2 S(y, u_1, u_2, d) \wedge C(x, r, u_1, u_2, x^+). \quad (6.7)$$

The now internal signals u_1 and u_2 are quantified to simplify the model, and it is done without losing any information since they are completely specified by the state of the controller and the input.

Fault Detection and Isolation

The diagnosis problem is basically to infer the possible values of the unobservable fault inputs and states from observations of the system. Procedures for fault detection and fault isolation using the basic operations of the relational framework are presented in [6].

Diagnosability Analysis

One of the main features of the DEDS approach to diagnosis, is the ability to analyse diagnosability properties. A fault is said to be detectable if there exists a transition in the system model that leads to a detection in a finite number of steps. Whether a fault is detectable and the transition necessary for detection can be automatically deduced from the system model under certain conditions.

We will say that the fault detection procedure is *ambivalent with respect to* $d_{i,k}$ when the normal value $d_{i,N}$ and the fault value $d_{i,k}$ of the fault variable d_i is in the estimation set simultaneously, i.e., when the fault *and* the normal behavior is consistent with the observations.

The state and input combinations for which the fault detection procedure is ambivalent with respext to $d_{i,k}$ can be computed as

$$A_{d_{i,k}}(x, u, y) = \exists x^+, d_i^+ M_i[d_i \mapsto d_{i,N}] \wedge M_i[d_i \mapsto d_{i,k}] \tag{6.8}$$

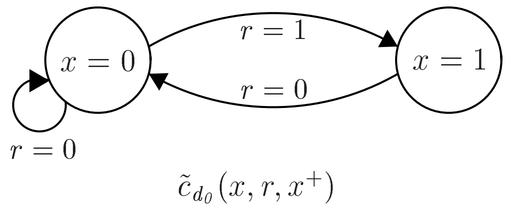
where $A_{d_{i,k}}$ stands for ambivalent with respect to the fault $d_{i,k}$. This calculation is done under a single fault assumption.

As an example of the final result of this kind of analysis, we can look at Figure 6.9. This means that the fault valve stuck closed can only be detected when the controller attempts to get flow through the system. This seems very reasonable. More interesting is perhaps the result for the fault valve stuck open, in Figure 6.10. Here we see that this fault is indetectable, due to the design of the controller.

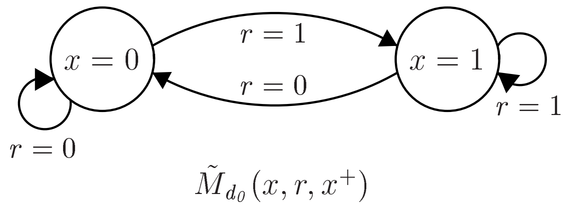
Fault Partitioning

In a system with many possible faults and a limited amount of sensors, it is often the case that the exact fault that has occured cannot be uniqely isolated. Without adding sensors or change something in the system to improve diagnosability, we have to accept that certain faults cannot be distinguished and define a fault partition, i.e., a set of sets of faults.

Definition 6.3.1 Isolatable faults
For the relational model $M(x, u, y, x^+, d^+)$, we will call the two faults $d_{i,k}$ and $d_{j,l}$ *isolatable* if there exists a controllable transition, i.e., values of x and u, in M which gives different behavior, i.e., outputs or next states, for the two faults. All fault variables d_s are assumed to have their normal value $d_{s,N}$ for $s \neq i, j$. □



(a) The transitions for which d_0 (valve stuck closed) cannot be detected.



(b) The transitions possible when $d = d_N$ or $d = d_0$.

Figure 6.9: The ambivalent and possible behavior with respect to d_0 (valve stuck closed).

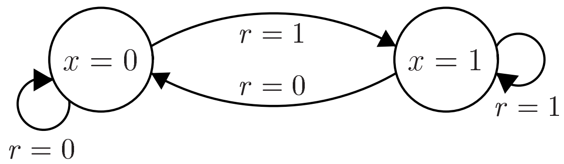
The property in Definition 6.3.1 can be checked as follows. Calculate the two relational models $b_{d_{i,k}}$ and $b_{d_{j,l}}$.

$$b_{d_{i,k}}(x, u, y, x^+) = M_i[d_i \mapsto d_{i,k}, d_i^+ \mapsto d_{i,k}] \tag{6.9}$$
$$b_{d_{j,l}}(x, u, y, x^+) = M_j[d_j \mapsto d_{j,l}, d_j^+ \mapsto d_{j,l}] \tag{6.10}$$

The relational model $b_{d_{i,k}}(x, u, y, x^+)$ represents the behavior of the system, under the single fault assumption, if the fault $d_{i,k}$ has occured. If $b_{d_{i,k}} = b_{d_{j,l}}$, i.e., the system has exactly the same behavior for both faults, then the errors $d_{i,k}$ and $d_{j,l}$, cannot be distinguished for any input/state sequence.

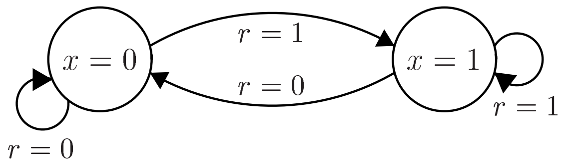
To find all pairs of faults that cannot be distinguished, we have to perform all possible pairwise comparisons. The finest possible fault partition, under the single fault assumption, for which the faults in different partitions still are distinguishable, then is given by partitioning the faults with identical behavior together.

Performing this procedure on the valve/pump example gives the mininal



$\tilde{c}_{d_2}(x, r, x^+)$

(a) The transitions for which d_2 (valve stuck open) cannot be detected.



$\tilde{M}_{d_2}(x, r, x^+)$

(b) The transitions possible when $d = d_N$ or $d = d_2$.

Figure 6.10: The ambivalent and possible behavior with respect to d_2 (valve stuck open).

partitioning

$$\{ \{ d_{1,0},\ d_{2,0} \},\ \{ d_{1,2} \},\ \{ d_{2,2} \} \} \tag{6.11}$$

where it is seen that pump stuck off and valve stuck closed cannot be distinguished.

Chapter 7

Applications

In this chapter some control and signal processing applications are presented. The common property of these research activities is that they are inspired by industrial problems and carried out in cooperation with industry.

7.1 Cellular Radio Systems

During the last years, the market of cellular radio systems has exploded. The driving incentive is to enable communication services irrespective of time and location. As the number of users and the demand for multimedia services increase, so does the need for efficient utilization of the available resources. Extensive planning is needed during the design phase of these systems. However, some decisions have to be considered while in operation.

A consequence of the limited availability of radio channels in the network, is that the same channel has to be assigned to many users. Thus a signal intended for a certain user will reach other users, disturb their connection and thereby degrade the quality, see Figure 7.1. A user with very good quality may consider to use a lower power and still have acceptable quality. The advantage is that he will disturb other users less, and thereby their quality is improved. Power control is essentially to do the same thing but in a controlled manner.

In ideal situations, the power control problem can be solved analytically, but in real cases several aspects that tend to blur the picture have to be considered.

- In practical cases the power can only be controlled based on local mea-

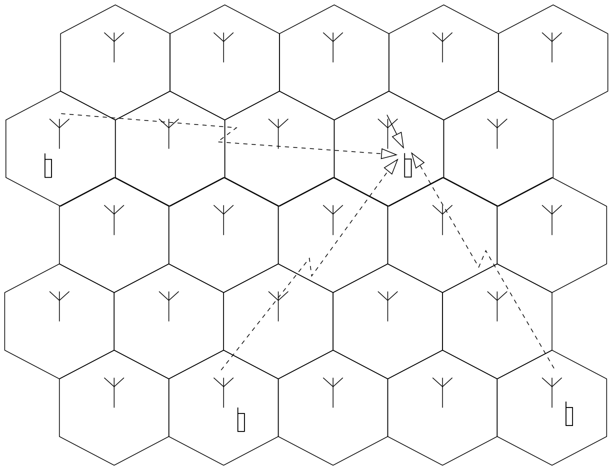


Figure 7.1: The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

surements and estimates.

- Measuring, estimation and control signaling takes time, which result in time delays in the system.

- The output power levels are limited to a given set of values due to hardware constraints. This includes quantization and saturation.

- Quality of Service is a very subjective quantity, and the choice of adequate quality measures is an important issue.

- Even if the optimal quality measure is found, this will most likely not be possible to measure. Thus it is important to extract as much relevant information from the available measurements.

Consider a system using orthogonal channels. If the channel allocation is fixed and orthogonality is preserved despite varying signaling conditions, the situation on one channel is independent of the situation on the others. These assumptions form the basis for the simulation environment presented in [31]. The cellular layout is described by a grid of hexagonal cells with equal radius. The base station antennas are omnidirectional and located in the center of the cells as seen in Figure 7.2. Analytical solutions are possible in simplified

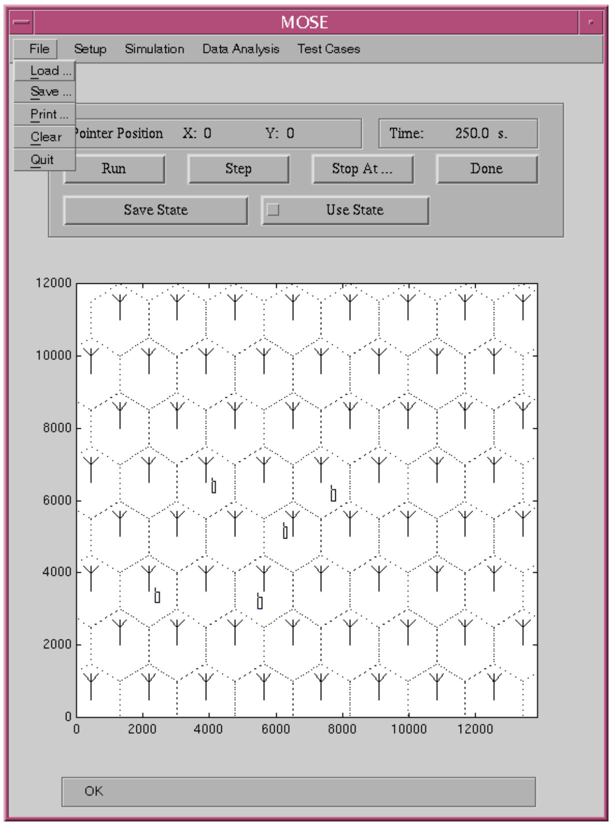


Figure 7.2: Simulation environment for power controlled mobile communication systems.

cases, but when analyzing the effects of power control subject to time delays, constraints and time-varying channels, such a tool provides valuable insight and intuition.

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

7.2 Robot Control

This project is carried out in cooperation with ABB Robotics within the competence center ISIS (Information Systems for Industrial Control and Supervision). The aim of the project is to study and develop methods for improvement of the performance of robot control systems. The project started in the middle of 1996 and during the first one and a half years the work has been concentrated on literature and simulation studies of Iterative Learning Control (ILC) which is a method that is applicable where the system is carrying out the same operation iteratively. A short introduction to the area of ILC is given in [56]. The structure of the problem that has been considered so far is given in Figure 7.3. The system G is controlled by a conventional control system including both feed-forward and feed-back, represented by the F_f and F respectively. In addition to the control signals generated by these blocks a correction signal ΔU_k is added. By evaluating the performance of the control system after one cycle it is possible to update the correction signal such that the error in the next cycle is reduced. In the simulation studies lin-

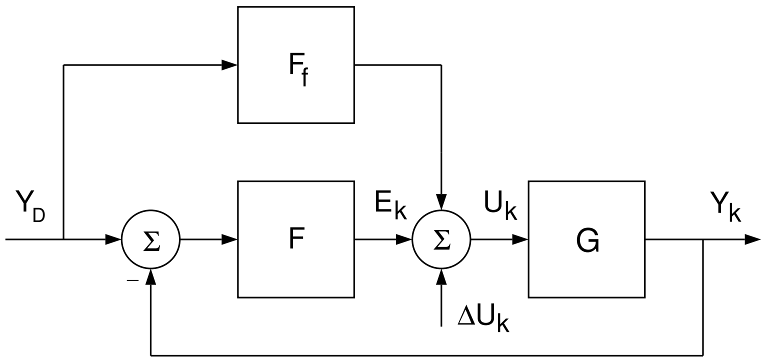


Figure 7.3: A control system with feed-forward, feed-back and an ILC correction signal

ear rigid body models of one- and two-arm manipulators have been studied, and different aspects of the way the correction signal is updated have been investigated. In particular the focus has been on convergence and robustness aspects and also the influence of load and measurement disturbances. Some results and experiences form the simulation studies are given in the conference papers [25] and [27] respectively.

In the next phase the aim is to test ILC on a commercial robot and therefore an ABB IRB 1400 was installed at the Division of Automatic Control in the middle of 1997. The robot is equipped with the control system S4C which does not have any facilities for application of ILC. Therefore a software interface between S4C and Matlab has been developed and a first version is now available. Using this interface ILC can be tested on the IRB 1400.

7.3 Control of Fluid Power Systems

During some years the control group has been cooperating with the Department of Mechanical Engineering in a project dealing with control of a flexible mechanical structure (lorry crane) controlled by fluid power actuators. A summary of this project is given in [70].

7.4 Friction Estimation in Cars

In a joint project between AB Volvo and Automatic Control, Linköping University, a prototype system for estimating the friction between tire and road in vehicles has been developed. 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 [12], and a broader presentation with particular attention to change detection is accepted for publication in *IEEE Control Systems Magazine*. A comparison of different change detection strategies and their evaluation is found in [33].

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.

Appendix A

Personnel

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Fredrik Tjärnström was born in 1973. He received his M.Sc. in Engineering Physics in 1997 from Linköping University.
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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

Dalius Navakauskas, Vilnius Technical University, Vilnius, Lithuania, was visiting researcher at the Division during November, 1996 - August, 1997.

Dorel Aiordachioaie, Dunarea de Jos Galati University, was visiting researcher at the Division during March - May, 1997.

Dr. Pierre Carrette, was a postdoctoral fellow at the Division University during April 1997 - May 1998.

Dr. Anna Lombardi, University of Siena, Siena, Italy, was visiting researcher at the Division during October - December 1997.

Dr. Alexander Pogromsky, St. Petersburg, Russia, was visiting researcher at the Division during October 1997 - July 1998.

Dr. Andrey Sokolov, St. Petersburg, Russia, was visiting researcher at the Division during November, 1997 - April 1999.

Appendix B

Courses

B.1 Undergraduate Courses

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

- *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+TB Mechanical Engineering and Engineering Biology Programs. 190 participants. Lecturer: Tomas McKelvey.

  Y Applied Physics and Electrical Engineering. 150 participants. Lecturer: Torkel Glad.

  D Computer Engineering Program. 120 participants. Lecturer: Johan Gunnarsson.

  Ie Industrial Engineering and Management, Electrical engineering variant. 90 participants. Lecturer: Tomas McKelvey.

  I Industrial Engineering and Management. 180 participants. Lecturer: Svante Gunnarsson.

- *Control Theory Y* (Reglerteori Y). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Multivariable systems, Fundamental limitations in feedback control systems, LQG-control, Loop transfer recovery, Loop shaping methods, Nonlinear systems, Optimal control. 80 participants. Lecturer: Lennart Ljung.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management Program. Multivariable systems, Sampled data systems, LQG-control. 25 Participants. Lecturer: Svante Gunnarsson.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Nonlinear systems, Signal processing. 20 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. 80 participants. Lecturer: Fredrik Gustafsson.

- *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. 35 participants. Lecturer: Inger Klein.

- *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. 120 participants. Lecturers: Tomas McKelvey et al.

- *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, 10 Participants. Lecturer: Fredrik Gustafsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Avaliable for several Engineering Programs. 250 Participants. Lecturer: Fredrik Gustafsson (Spring 1997) and Niclas Bergman (Fall 1997).

The computer is an important tool in control education, and all courses have computer supported problem solving sessions. In some of the courses also the exam is carried out with the computer available. A presentation of some experiences concerning computer support in control education is given in [28].

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

- *Automatic control, EI* (Electrical Engineering) 5 units, 40 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 participants. Contents: Sequential control and logic controllers. A typical industrial control system. Lecturer: Kent Hartman.

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

- *Linear Systems*. Lecturer: Torkel Glad. Literature: W. J. Rugh, Linear System Theory, Prentice Hall and T. Kailath, Linear Systems, Prentice Hall.

- *Fundamental Limitations in Filtering and Control* Lecturer: M. Seron and M. Braslavsky. Literature: Lecture notes.
- *Convex Optimization*. A series of seminars by the participants. Literature: Lecture notes.

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 10 Intel-based laptop computers. In the laboratory, mainly used by students in the different courses, there are a lot of different processes and 14 Intel-based computers for measurement and control. The students also got 24-hours access to 64 SPARC-stations 10 computers in an Ethernet based computer network.

Comments and questions on the equipment can be directed to Mattias Olofsson.

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)
- 24 Sun Ultra 1
- 3 Sun SPARCstation 20
- 3 Sun SPARCstation 10
- 8 Sun SPARCstation 5
- 2 Dell OptiPlex PC:s

- 1 HP LaserJet 4 Si/MX Postscript laser printer
- 1 HP ColorJet Postscript laser printer
- 2 HP LaserJet 5 MPPostscript laser printer
- 1 Tektronix Phaser 350 solid ink-jet color printer

The Sun workstations run Solaris 2.6 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 Matlab, Maple, Mathematica, 20sim, 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:

- 5 Dell Latitude (Pentium and Pentium II of various speed)
- 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
- 8 Dell Workstation 400 with dSPACE signal processing cards
- 6 Pentium 120 PC
- 3 AST Bravo 486 computers with Allan Bradley SLC500 PLC system
- 1 LEO 386 computers with Metrabyte Dash 16 interfaces (A/D, D/A and digital I/O).
- 1 HP LaserJet 4 MP laser printer

Appendix D

Seminars

Frequency Domain Properties of Discrete Time Zeros. **Bernardo A. León de la Barra S.**, Department of Electrical Engineering, Universidad de Chile, January 22, 1997.

Mini-course on max-plus algebra and its application to analysis and control of discrete event dynamical systems. **Dr. Nikolai K. Krivulin**, St Petersburg, Russia, February 1997.

Closed-loop ID in general. **Dr. Paul van den Hof**, TU, Delft, the Netherlands, January 27, 1997.

Co-Channel Source Separation: Some Experimental Results. **Professor Lee Swindlehurst**, Brigham Young University, Provo, Utah USA, February 13, 1997.

Load control and network synchronization - some control theory related challenges within AXE. **Hans Alberg**, Ericsson Utvecklings AB, Stockholm, February 20, 1997.

Discrete Event Dynamic Systems: Logical Analysis and Synthesis. **Bruce Krogh**, Carnegie Mellon University, March 20, 1997.

Future diagnostics and emission requirements. **Joel Duhr**, Delphi Automotive Systems (GM), Luxemburg, February 6, 1997.

Open systems architecture for engine control. **Anders Göras**, Mecel AB, Åmål, February 6, 1997.

Frequency multiband decomposition of H-infinity control problem and Bode diagrams. **Dr. Andrey Barabanov**, St Petersburg University, St Petersburg, Russia, March 4, 1997.

Sensor Fusion for Mobile Robot Navigation - A Subjective Discussion. **Professor Bo Wahlberg**, Automatic control, Royal Institute of Technology, Stockholm, April 10, 1997.

Neural networks applications in signals processing and systems identification. **Dr. Dorel Aiordachioaie**, "Dunarea de Jos" Galati University Electrical Engineering Faculty. April 24, 1997.

An adaptive notch filter with guaranteed stability properties. **Dr. Romeo Ortega**, Laboratoire des Signaux et Systemes, CNRS-SUPELEC, April 14, 1997.

NDB-Cluster - A Parallel Data Server for Telecom. **Mikael Ronström**, Ericsson Utvecklings AB, Stockholm, April 17, 1997.

Discrete and continuous adaptive control of nonlinear oscillations and chaos. **Alexander L. Fradkov**, Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St.Petersburg, May 6, 1997.

Final year projects in control engineering in the university of St. Petersburg. **Olga Tomtchina**, St.Petersburg Machine Building Institute, Dept. of Electrotechnics and Manufacturing Systems Automation, May 7, 1997.

Formal Verification in a Commercial Setting. **Dr. Robert Kurshan**, Bell Laboratories, May 21, 1997.

Guaranteeing Real-Time Traffic Through an ATM Network. **Professor Hans A. Hansson**, Department of Computer Systems, Uppsala University, May 15, 1997.

Supervisory Control of the Untimed Behaviors of Petri Net Models of Discrete Event Dynamic Systems. **Professor Ramavarapu S. Sreenivas**, Department of General Engineering, University of Illinois, May 15, 1997.

Research at Ericsson Radio, Kista. **Dr. Sören Andersson**, Ericsson Radio, Kista, May 29, 1997.

Integrated Adaptive Control for Space Robotic Systems. **Dr. Liron Ehrenwald**, Aerospace Engineering, Technion, Haifa, Israel, May 18, 1997.

Failure Diagnosis of Discrete Event Systems. **Dr. Stephane Lafortune**, University of Michigan, August 11, 1997.

Fundamental Limitations in Filtering and Control. 2-day Workshop: **Dr. Maria Seron and Dr. Julio Braslavsky**, ECE Department University of California, Santa Barbara, CA, USA.

Finite sample complexity of least squares system identification. **Professor Erik Weyer**, The University of Melbourne, September 3, 1997.

Dead-beat controllability for a class of parallelly connected polynomial systems. **Dr. Dragan Nesic**, CESAME, Louvain la Neuve, Belgium, September 10, 1997.

Control and System Theory of Hybrid Systems. **Professor Jan van**

Schuppen, CWI, Amsterdam, The Netherlands, September 11, 1997.

Orthonormal Bases for System Identification: Useful or not?. **Dr. Brett Ninness**, University of Newcastle, Newcastle, Australia, September 25, 1997.

Posterior Cramer-Rao Bounds for Discrete-Time Nonlinear Filtering. **Petr Tichavsky**, Inst. of Information Theory and Automation, Prague, Czech Republic, September 18, 1997.

State Bond Prediction Using Neural Networks. **Dr. Anna Lombardi**, Universita‘ di Siena, Siena, Italy, October 16, 1997.

Iterative Feedback Tuning: Theory and Practice. **Dr. Håkan Hjalmarsson**, S3, Royal Institute of Technology, Stockholm, October 21, 1997.

On the relationship between the closed loop poles and feedback gains in the design of multi input linear systems. **Dr. Kjell Nordström**, Uppsala University, October 21, 1997.

Control systems. **Dr. Krister Forsman**, ABB Corporate Research, Malmö, Sweden, October 21, 1997.

Automatic Driving with Image Processing. **Andreas Kuehnle**, CTS, Borlänge, Sweden, November 13, 1997

On some specific problems of control of oscillations. **Dr. Alexander Pogromsky**, Russian Academy of Science, St Petersburg, November 12, 1997.

Practical Utility of Asymptotic Analysis - A Case study. **Dr. Brett Ninness**, University of Newcastle, Australia, November 20. 1997.

Presentation av ABB Robotics styrsystem S4 - ur datalogisk och systemteknisk synvinkel. **Dr. Torgny Brogård and Peter Eriksson**, ABB Robotics, Västerås, Sweden, December 4, 1997.

An experimental tool for semi-physical modeling in conditions of insufficient data measurements: application to IC engine control problems. **Dr. Andray Sokolov**, St Petersburg, Russia, November 27, 1997.

Appendix E

Travel and Conferences

Lennart Ljung visited ABB Corporate Research, Baden, Switzerland on January 12-22 and Stanford University on Febrary 17-21. June 5-7 he visited University of Edmonton, Alberta and June 9-11 he participated in AdChem'97 in Banff. He participated in ACSAP 97 in Prague on June 24-26 and the ECC in Brussels on July 1-3. He participated in the IFAC Symposium on System Identification in Kitakyoshi, Japan on July 7-11 and visited the University of Oita, Kyoto University and Tokyo Institute of Technology during July 14 - 17. He participated in the meeting of the European Research Network on System Identification (ERNSI) September 8-10. December 7-8 he visited Arizona State University and December 10-12 he participated in the 35th IEEE Conference on Decision and Control in San Diego, CA.

Niclas Bergman participated in SYSID'97 Japan, ERNSI'97 Stockholm and CDC'97 in San Diego, Ca.

Jonas Blom participated in the IEEE Vehicular Technology Conference (VTC'97), Phoenix, AZ, USA. May 1997. He also took part in the Nordic MATLAB Conference '97 in Stockholm, Sweden.

Valur Einarsson participated in International Summer School on Verification of Digital and Hybrid Systems - An Advanced Study Institute of the NATO Science Committee Belek/Antalya, Turkey May 26-June 6, 1997

Urban Forssell participated in SYSID'97 Japan, ERNSI'97 Stockholm and CDC'97 in San Diego, Ca.

Torkel Glad participated in COSY Workshop on Control of Nonlinear and Uncertain Systems, Zurich, Switzerland, January 17-19, 1997, COSY Workshop on Applied Problems in Nonlinear Control, Brussels, Belgium, June 30, 1997 and the European Control Conference, ECC97, Brussels, Belgium, July

1-4, 1997

Fredrik Gunnarsson participated in the IEEE Vehicular Technology Conference (VTC'97), Phoenix, AZ, USA. May 1997. He also took part in the Nordic MATLAB Conference '97 in Stockholm, Sweden.

Svante Gunnarsson visited ABB Robotics, Västerås May 27, Siemens, Stockholm, March 26, Saab Dynamics, Jönköping, September 30. He participated in the European Control Conference, Brussels, Belgium, July 1-4, 1997, IFAC Symposium on Advances in Control Education, Istanbul, Turkey, July 14-16, and the IFAC Symposium on Robot Control, Nantes, France, September 3-5.

Fredrik Gustafsson attended the conferences ECC in Brussel and SYSID in Kobe, Japan, both in July. He spent three weeks in March with the department of ELEC, Vrije Universiteit Brussel on an invitation from Johan Schoukens.

Anna Hagenblad participated in ERNSI in September, 1997.

Kent Hartman participated 9-10 June 1997 in "Nya Ingenjörs- och civilingenjörsutbildningar". LiTH Linköping, 14-17 June 1997: "Teaching Science for Technology", KTH Stockholm, 11-12 September 1997: "Linköping Biomedical Engineering Symposium", LiTH Linköping and 17-18 November 1997: "Nya Ingenjörs- och civilingenjörsutbildningar", LiTH Linköping.

Anders Helmersson visited the Institute of Systems Science of the Chinese Academy of Sciences, Beijing, China, October 14, 1997.

Tomas McKelvey participated in the American Control Conference, Albuquerque, NM, USA, June 4-6 and in the IFAC Symposium on system identification in Kitakyoshi, Japan on July 7-11. On September 8-10 he attended the workshop of the European research network on system identification, Stockholm, Sweden. On September 14-17 he took part of the 16th Biennial Conference on Mechanical Vibration and Noise in Sacramento, CA. December 10-12 he participated in the 35th IEEE Conference on Decision and Control in San Diego, CA.

Mikael Norrlöf participated in Robotikdagarna, Linköping, 10-11 June 1997, ECC, Brussels, 1-4 July 1997 in IFAC 5th symposium on robot control, SYROCO'97, 3-5 September 1997 and he also participated in a tutorial "Friction and Control" in connection with SYROCO'97.

Mats Jirstrand was a guest researcher at Information Systems Laboratory at Stanford University, California, USA, April 21 - June 2 and October 1 - November 7, 1997. He also visited Wolfram Research, Champaign, Illinois, USA, October 30, 1997. On June 4 - 6 he participated in the 1997 American

Control Conference, Albuquerque, New Mexico, USA.

Ulla Salaneck participated in Rikssekreterarträffen at Reykjavik, Island, September 16 - 19, 1997 and in "The Office professional 2" in London October 28 - October 31, 1997.

Appendix F

Lectures by the Staff

Magnus Andersson: *Noise Robust Actuator Placement on Flexible Structures*, 36th IEEE Conference on Decision and Control, San Diego, CA, December 1997.

Magnus Andersson: *Avoiding mode pairing when updating finite element models*, Proc. of the 11th IFAC Symposium on System Identification, Kitakyushu, Japan, July, 1997.

Niclas Bergman: *A Bayesian Approach to Terrain-aided Navigation*, 11th IFAC Symposium on System Identification, Kitakyushu, Japan, July, 1997.

Niclas Bergman: *Point-mass filter and Cramer-Rao bound for Terrain-Aided Navigation*, 36:th IEEE Conf. on Decision and Control, San Diego, Ca. December, 1997

Jonas Blom: *Mobile Communication Systems - An Object-Oriented Simulation Environment*, Nordic MATLAB Conference '97, Stockholm, Sweden, October 27-28 1997.

Krister Edström: *Modelling and simulation of a switched power converter* Third Int. Conf. on Bond Graph Modeling and Simulation (ICBGM'97), 1997

Urban Forssell: *Tracking Time-varying Systems: Revisiting Some Basic Trade-offs*, IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July, 1997.

Urban Forssell: *Combining Semi-physical and Neural Network Modeling: An Example of Its Usefulness*, IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July, 1997.

Urban Forssell: *Variance Results for Closed-loop Identification Methods*, The 35th IEEE, Conference ond Decision and Control, San Diego, CA, December 11, 1997.

Torkel Glad: *Stabilizable regions of unstable systems*, COSY Workshop on Control of Nonlinear and Uncertain Systems, Zurich, January 18 1997.

Torkel Glad: *Solvability of differential algebraic equations and inequalities: an algorithm*, ECC97, July 1 1997.

Johan Gunnarsson: *Tools for Verification of a Large Discrete System*, Second International Mathematica Symposium, Rovaniemi, Finland, 2 July, 1997

Fredrik Gunnarsson: *Mobile Communication Systems - An Object-Oriented Simulation Environment*, Nordic MATLAB Conference '97, Stockholm, Sweden, October 27-28 1997.

Svante Gunnarsson: *Computer Supported Control Education from a Linköping Perspective*, IFAC Symposium on Advances in Control Education, Istanbul, Turkey, July 14.

Fredrik Gustafsson: *A comparative study on change detection for some automotive applications*, European Control Conference '97. Brussels, Belgium, July, 1997.

Fredrik Gustafsson: *Consistent low-complexity estimation of active parameters in large linear regressions*, SYSID'97, July, Japan.

Fredrik Gustafsson: *A generalization of MDL for choosing adaptation mechanism and design parameters in identification*, SYSID'97, July, Japan.

Fredrik Gustafsson: *Friction estimation in cars*, Dept ELEC, Vrije Universiteit Brussel, March 1997.

Anders Helmersson: *Applications of real-μ gain scheduling*, seminar at the Control Engineering Laboratory, Chalmers University of Technology, Göteborg, Sweden, 25 April, 1997.

Anders Helmersson: *Theory and applications of real-μ gain scheduling*, seminar at the Institute of Systems Science of the Chines Academy of Sciences, Beijing, China, October 14, 1997.

Mats Jirstrand: *Semidefinite Programming (SDP) and Applications*, Wolfram Research, Champaign, Illinois, USA, October 30, 1997.

Mats Jirstrand: *Curve Following for Nonlinear Dynamic Systems Subject to Control Constraints*, The American Control Conference, Albuquerque, New Mexico, USA, June 5, 1997.

Peter Lindskog: *Utilizing prior knowledge in system identification: semiphysical, neural and fuzzy approaches*, Signals, Sensors and Systems, KTH, Stockholm, March 24, 1997.

Lennart Ljung: *From Data To Model: An overview of System Identifica-*

tion, ABB Corporate research. Baden, Switzerland, January 21, 1997.

Lennart Ljung: *Hybrid Systems Modelling – Some new (Linköping) approaches*, Baden, Switzerland, January 22, 1997.

Lennart Ljung: *From Data to Model – Status of System Identification*, ISL Industrial Affiliates meeting, Stanford University, February 17, 1997.

Lennart Ljung: *A least squares interpretation of subspace identification methods*, Stanford University, February 19, 1997.

Lennart Ljung *System Identification – A short course*, University of Edmonton, Canada, June 6 - 7, 1997.

Lennart Ljung: *Non-linear black box models in system Identification*, Plenary Lecture at the IFAC Symposium on Advanced Control of Chemical Processes, AdChem97', Banff, Canada, June 10, 1997.

Lennart Ljung: *System Identification*, Plenary lecture at the first European Conference on Signal Analysis and Prediction. ECSAP 97, Prague, June 24, 1997.

Lennart Ljung: *Interpretation of subspace methods. Consistency analysis*, IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July 9, 1997.

Lennart Ljung: *Identification in closed loop. Some aspects of direct and indirect methods*, IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July 9, 1997.

Lennart Ljung: *Developments for the system identification toolbox in MATLAB*, IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July 10, 1997.

Lennart Ljung: *What are the challenges for system identification? The past, present and future*, Panel discussion at IFAC Symposium on System Identification, SYSID'97, Kitakyoshi, Japan, July 11, 1997.

Lennart Ljung: *Black-box non-linear models in System Identification*, Oita University, Japan, July 14, 1997.

Lennart Ljung: *Closed loop identification revisited*, Kyoto University, Japan, July 15, 1997.

Lennart Ljung: *Black-box non-linear models in System Identification*, Tokyo Institute of Technology, Japan, July 1997.

Lennart Ljung *Closed Loop Identification revisited*, Cambridge University, October 30, 1997.

Lennart Ljung *Non-linear black box models in system identification*, Arizona State University, Phoenix, AZ. December 8, 1997.

Lennart Ljung: *Identification, Model Validation and Control*, Plenary Lecture, The 35th IEEE, Conference ond Decision and Control, San Diego, CA, December 11, 1997.

Tomas McKelvey: *$\mu-$Synthesis with Matrix Valued Scalings - Algorithms and Examples*, American Control Conference, Albuquerque, NM, USA, June 4, 1997.

Tomas McKelvey: *Frequency Domain Maximum Likelihood Identification*, IFAC Symposium on System Identification, Kitakyushu, Japan, July 11, 1997.

Tomas McKelvey: *Identification in frequency domain - The MIMO ML-estimator and Some convergence results*, ERNSI workshop, Stockholm, Sweden, September 1997.

Tomas McKelvey: *Frequency Domain System Identification with Instrumental Variable Based Subspace Algorithm*, 16th Conference on Mechanical Vibration and Noise, ASME, Sacramento, CA, USA, September 15, 1997.

Tomas McKelvey: *System identification using an over-parametrized model class - Improving the optimization algorithm*, The 35th IEEE, Conference ond Decision and Control, San Diego, CA, December 11, 1997.

Mikael Norrlöf: *Robust Control, an overview*, Seminar ABB Robotics Västerås, March 25, 1997.

Mikael Norrlöf: *Using iterative learning control to get better performance of robot control systems*, Robotikdagarna, Linköping, June 10-11, 1997.

Mikael Norrlöf: *On the use of learning control for improved performance in robot control systems*, ECC, Brussels, 1-4 July 1997.

Mikael Norrlöf: *Some Experiences of the Use of Iterative Learning Control for Performance Improvement in Robot Control Systems*, SYROCO'97, September 3-5, 1997.

Jan Palmqvist: *Change Detection Design for Low False Alarm Rates, IFAC Symposium on Fault Detection*, Supervision and Safety for Technical Processes, Kingston upon Hull, UK August 28, 1997.

Appendix G

Publications

Ph.D. Theses

[1] Johan Gunnarsson. *Symbolic Methods and Tools for Discrete Event Dynamic Systems*. PhD thesis, Linköping University, May 1997.

Licentiate Theses

[2] Jan Palmqvist. On integrity monitoring of integrated navigation systems. Licentiate thesis LIU-TEK-LIC-1997: Linköping Studies in Science and Technology. Thesis No 600, Department of Electrical Engineering, Linköping, Sweden, February 1997.

[3] Anders Stenman. Just-in-Time models with applications to dynamical systems. Licentiate thesis LIU-TEK-LIC-1997:02. Thesis No. 601, Department of Electrical Engineering, Linköping, Sweden, March 1997.

[4] Magnus Andersson. Experimental design and updating of finite element models. Licentiate thesis LIU-TEK-LIC-1997: Linköping Studies in Science and Technology. Thesis No 611, Department of Electrical Engineering, Linköping, Sweden, April 1997.

[5] Urban Forssell. Properties and usage of closed-loop identification methods. Licentiate thesis LIU-TEK-LIC-1997: Linköping Studies in Science and Technology. Thesis No 641, Department of Electrical Engineering, Linköping, Sweden, September 1997.

[6] Magnus Larsson. On modeling and diagnosis of discrete event dynamic systems. Licentiate thesis LIU-TEK-LIC-1997:49 Linköping Studies in Science and Technology. Thesis No 648, Department of Electrical Engineering, Linköping, Sweden, October 1997.

[7] Niclas Bergman. Bayesian inference in terrain navigation. Licentiate thesis LIU-TEK-LIC-1997:50 Linköping Studies in Science and Technology. Thesis No 649, Department of Electrical Engineering, Linköping, Sweden, November 1997.

Books

[8] S. T. Glad and L. Ljung. *Reglerteori - Flervariabla och olinjära metoder*. Studentlitteratur, 1997.

[9] P. Lindskog, S. T. Glad, and L. Ljung. *Modellbygge och simulering - Övningsbok*. Studentlitteratur, 1997.

Journal Papers

[10] P. Lindskog. Fuzzy identification from a grey box modeling point of view. In H. Hellendoorn and D. Driankov, editors, *Fuzzy Model Identification – Selected Approaches*, pages 3–50. Springer, 1997.

[11] M. Jirstrand. Nonlinear control system design by quantifier elimination. *Journal of Symbolic Computation*, 24(2):137–152, August 1997.

[12] F. Gustafsson. Slip-based estimation of tire - road friction. *Automatica*, 33(6), 1997.

[13] F. Gustafsson, S. Gunnarsson, and L. Ljung. On time–frequency resolution of signal properties using parametric techniques. *IEEE Trans. on Signal Processing*, 45(4):1025–1035, 1997.

[14] B. Ninness and F. Gustafsson. A unifying construction of orthonormal bases for system identification. *IEEE Trans. on Automatic Control*, 42(3), 1997.

[15] L. Ljung and L. Guo. The role of model validation for assessing the size of the unmodeled dynamics. *IEEE Trans.Automatic Control*, AC-42(9):1230–1240, 1997.

[16] L. Guo, L. Ljung, and G.-J. Wang. Necessary and sufficient conditions for stability of LMS. *IEEE Trans.Automatic Control*, AC-42(6):761–771, 1997.

[17] L. Ljung and L. Guo. Classical model validation for control design purposes. *Mathematical Modelling of Systems*, 3(1):27–42, 1997.

Conference Papers

[18] N. Bergman. A Bayesian approach to terrain-aided navigation. In *Proc. of the 11th IFAC Symposium on System Identification*, volume 3, pages 1531–1536, Kitakyushu, Japan, July 1997.

[19] N. Bergman, L. Ljung, and F. Gustafsson. Point-mass filter and Cramer-Rao bound for terrain-aided navigation. In *Proc. 36:th IEEE Conf. on Decision and Control*, volume 1, pages 565–570, San Diego, California, USA, December 1997.

[20] M. Andersson. Noise robust actuator placement on flexible structures. In *Proc. 36th IEEE Conference on Decision and Control*, pages 1958–1959, San Diego, California, USA, December 1997.

[21] U. Forssell and L. Ljung. Tracking time-varying systems: Revisiting some basic trade-offs. In *Proc. of the 11th IFAC Symposium on System Identification*, volume 4, pages 1759–1764, Kitakyushu, Japan, 1997.

[22] M. Andersson and T. Abrahamsson. Avoiding mode pairing when updating finite element models. In *Proc. of the 11th IFAC Symposium on System Identification*, volume 1, pages 207–212, Kitakyushu, Japan, July 1997.

[23] U. Forssell and P. Lindskog. Combining semi-physical and neural network modeling: An example of its usfulness. In *Proc. of the 11th IFAC Symposium on System Identification*, volume 4, pages 795–798, Kitakyushu, Japan, 1997.

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Appendix I

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