LINKÖPING UNIVERSITY
DIVISIONS OF AUTOMATIC CONTROL AND COMMUNICATION SYSTEMS
ACTIVITY REPORT
2003

Contents

Chapter 1

Introduction

The Divisions of Automatic Control and Communication Systems consist of some thirty persons. 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:

- *System Identification*: We are interested in a number of aspects ranging from industrial applications, to aspects of the fundamental theory and properties of algorithms.

- *Non-Linear and Hybrid Systems*: 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. Hybrid systems is an important and emerging field covering problems of how to deal with systems with both discrete and continuous phenomena.

- *Sensor Fusion*: Techniques to merge information from several sensors are of increasing importance. We are involved in four different industrial application of this kind, at the same time as we try to abstract the common underlying ideas. Particle filters play an important role in this context.

- *Diagnosis and Detection Problems* are very important in today's complex automated world. Within the Competence Center ISIS we work with several industrial problems of this kind.

- *Communication Applications*: We have several applied and theoretical projects that deal with communication systems.

- *Robotics Applications*: Within ISIS we have a close cooperation with ABB Automation Technology Products – Robotics.

- *Optimization for Control and Signal Processing*: Convex optimization techniques are becoming more and more important for various control and signal processing applications. We study some such applications, in particular in connection with model predictive control.

Details of these research areas are given in the corresponding sections of this report.

We thank the Swedish Research Council (VR), the Swedish Agency for Innovation Systems (VINNOVA) and the Foundation for Strategic Research (SSF) for funding a major part of our research.

The Control and Communication Divisions take active part in the VINNOVA Competence Center ISIS (Information Systems for Industrial Control and Supervision), whose Director is Lennart Ljung. The ISIS Center started in November 1995. Phase III of this Competence center started January 1, 2001 and lasted to the end of 2003. Phase IV will cover 2004 and 2005.

The divisions are also central partners 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 Löfberg, Jacob Roll, Jonas Elbornsson and Ola Härkegård defended their PhD theses. Moreover, Erik Geijer-Lundin, Frida Gunnarsson, Martin Enqvist, Tomas Schöön, and Svante Björklund defended their Lic. Eng. dissertations.

Lennart Ljung received the 2003 Hendryk W. Bode Lecture Prize "for seminal contributions to identification and adaptive control."

Our long time co worker, Professor Mille Millnert, who started his career as a graduate student at the Division of Automatic Control in 1977 was appointed president of Linköping University on October 1, 2003.

In the following pages the main research results obtained during 2003 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

Figure 1.1: Lennart Ljung receives the Hendryk W. Bode Lecture Prize from Cheryl Schrader, chairman of the IEEE Control Systems Society, at the CDC'03 at Maui, Hawaii

Figure 1.2: Mille Millnert during the president inaguration ceremony at Linköping University

charge, most easily from our web-site. The next chapter describes how you can search for our publications in our data base and download any technical report.
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 Salaneck.

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 web 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, Joakim Svensén:

`joasv@isy.liu.se`

2.2 Publications Data Base

Selecting "Publications" in our web pages gives access to our publications data base. See Figure 2.1. It allows you to search for publications by author, area, year and/or publication type. You can also search for words in the title. The result of the search is given either as a clickable list of publications (Choose HTML) or a list of BibTeX items (Choose Bibtex). See Figure 2.2 for an example of a search result. Clicking on the publication items brings you to the home page of the publication with further information. See Figure 2.3. Department reports can always be downloaded from the home page, while articles and conference papers refer to a related department report that can be downloaded in .ps or .pdf format.

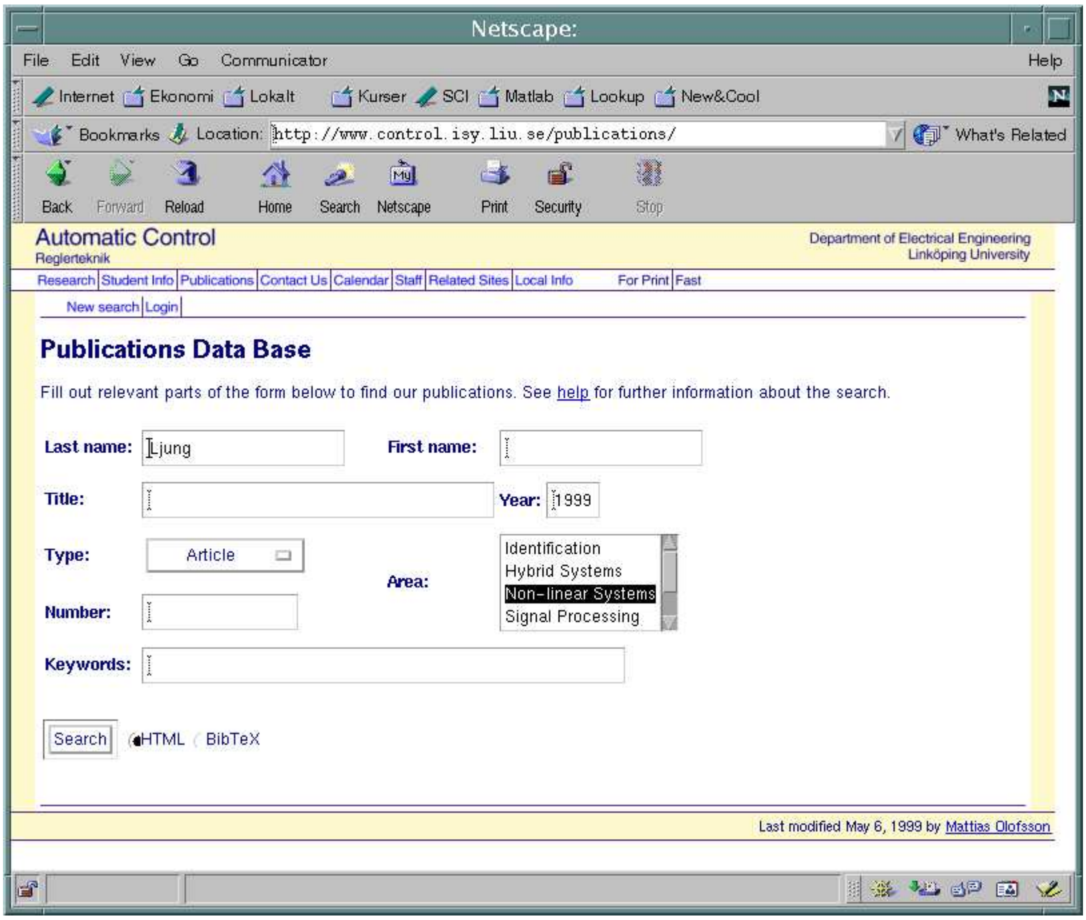


Figure 2.1: The publications data base interface

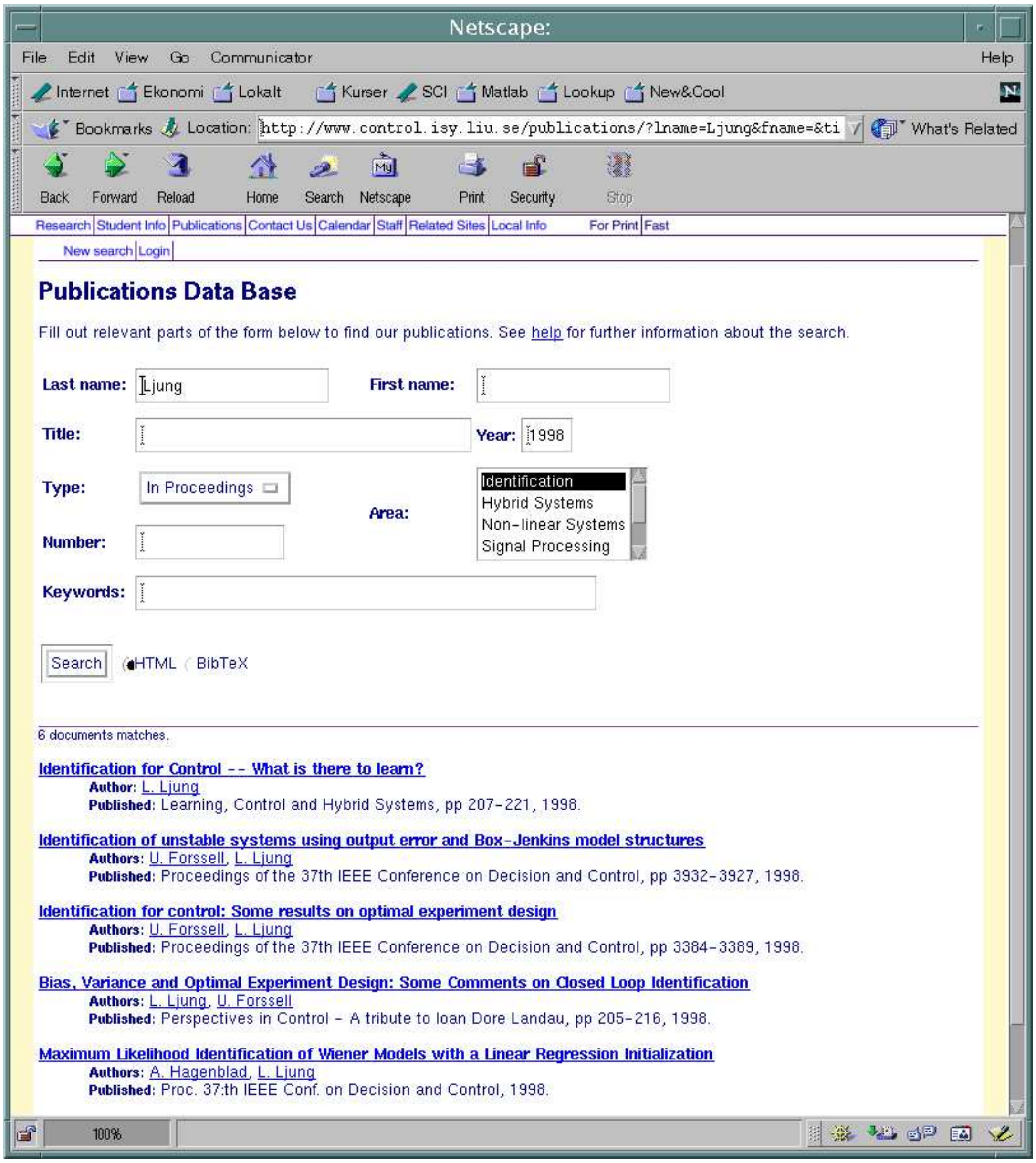


Figure 2.2: Example of search result

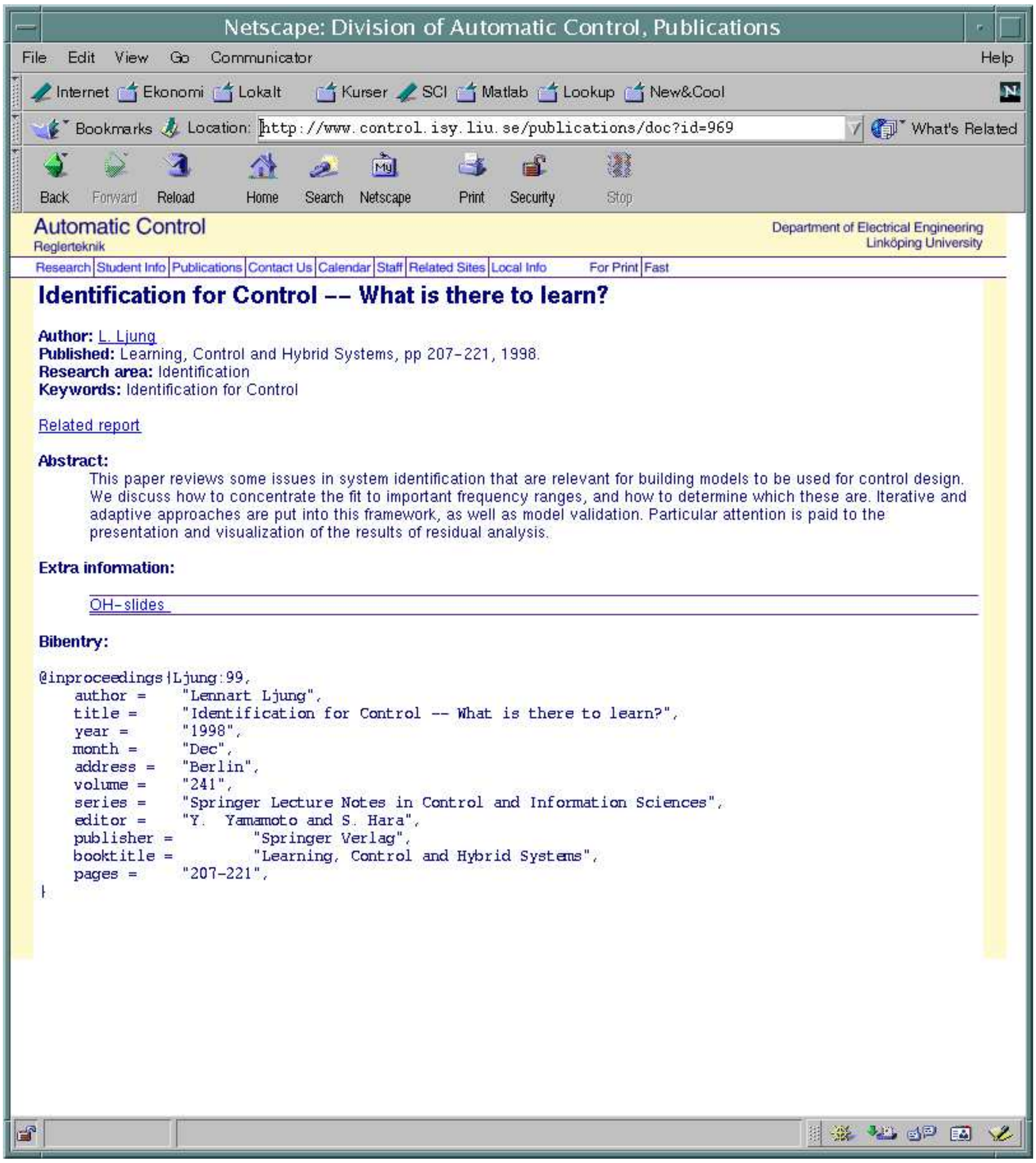


Figure 2.3: Example of a publication home page

Chapter 3

System Identification

3.1 Introduction

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

During 2002, one PhD-thesis, [2] and two licentiate theses, [6], and [9] have been finished in this area. These will be described in the next few sections.

3.2 Nonlinear System Identification via Direct Weight Optimization

A major part of Jacob Roll's PhD thesis deals with estimation of response surfaces with applications to non-linear black-box identification. The basic nonlinear identification problem considered here can be phrased as follows: Assume that we are given data $y(t)$ and $\varphi(t)$, $t = 1, \ldots, N$ from the unknown nonlinear system

$$y(t) = f(\varphi(t)) + e(t)$$

where $e(t)$ is a noise term with known variance σ^2. Estimate $f(\varphi^*)$ for a given point φ^*.

This type of identification problems arise, e.g., in the model-on-demand framework, where the main idea is not to bother about building a global model for a (possibly very complex) system, but instead keep a database of experimental data and build local models at specific points φ^* only when they are needed.

A wide-spread technique to model nonlinear mappings is to use basis function expansions (wavelets, neural networks, etc.). It is a well known fact that if the basis functions are *a priori* fixed, so that the model is linear in the parameters, this will lead to a least-squares estimate that is linear in the observed variables $y(t)$, i.e.,

$$\hat{f}(\varphi^*) = \sum_{t=1}^{N} w_t y(t) \tag{3.1}$$

where the weights w_t may depend on the point φ^*, on what basis function expansion has been used, and on the noise variance σ^2.

We can then instead turn the question around: If the true function f belongs to a given function class $\mathcal{F}$, for given φ^* and σ^2, what are the best weights w_t we can choose?

The point of posing the question in this way is that we now can use much more general function classes $\mathcal{F}$ than the ones described by the finite basis function expansions. In practice, of course, the true system function can seldom be exactly described by a finite basis function expansion, and this discrepancy can be captured by using a function class that allows a certain deviance from the parameterized functions. In other words, we can for instance state that the true function locally could be well approximated by a basis function expansion, and give bounds for the approximation errors.

Using a minimax framework, the problem of finding the optimal estimator (3.1) can now be formulated as a convex optimization problem, which can efficiently be solved.

For certain function classes (e.g., functions having a Lipschitz bounded derivative), several interesting properties have been shown in [54, 2] and [129]. For instance, for the mentioned class, it turns out that the weights will be nonzero only on a compact set, and that they will be described by (at most) two paraboloids. Asymptotic optimality has also been shown for some specific cases.

The case when bounds on the estimated function and its derivatives are known *a priori* has been studied in [53, 2], and it is shown that one can sometimes, but not always, benefit from this extra information. The problem of estimating the function derivatives is also considered.

3.3 Identification and Verification of Piecewise Affine Systems

Roll's thesis also contains a discussion of Hybrid systems, in the form of piecewise affine systems. Piecewise affine systems are composed of several affine subsystems, between which switchings occur at different occasions. Such systems are obtained, for instance, whenever an otherwise linear system contains bounded signals, dead-zones, or is controlled by discrete control laws. Piecewise affine systems can be found in many applications, and the research activities in the field have increased in the last decade.

Identification of piecewise affine systems is an area that is related to many other research fields within nonlinear system identification, and one can find several different methods and approaches which are applicable, or at least related to the piecewise affine system identification problem. However, until recently there have been few attempts to design special-purpose algorithms for these kinds of systems. In [60, 2], such an algorithm, based on mixed-integer programming, is presented. This approach guarantees that an optimal model is found, at a price of greater computational complexity. To reduce the complexity, one can either restrict the model class or use a suboptimal optimization procedure. Both these alternatives have been investigated. In particular, using piecewise affine Wiener models allows the complexity of the identification problem to be reduced considerably.

Another important issue is verification of piecewise systems. For safety or other reasons, one often needs to make sure, e.g., that certain states are never reached. A problem arises here if there are model errors — can we then trust the verification results? [2] suggests a verification method, where also bounds on the allowed model errors are computed. This method has also been described in previous annual reports.

3.4 Linear models of nonlinear systems

Martin Enqvist's licentiate thesis [6] describes and analyzes the properties of linear time-invariant (LTI) approximations of nonlinear systems. Systems with stationary stochastic input and output signals and LTI approximations that are optimal in the mean-square error sense have been studied. The reason for this choice of approximation type is that parameter estimates obtained by the prediction error method under fairly general conditions will approach values that correspond to mean-square error optimal LTI models when the number of measurements tends to infinity. The optimal LTI model is in [6] called the LTI Second Order Equivalent (LTI-SOE), since it can explain the second order properties of the input and output signals.

Although LTI approximations of general, possibly nonlinear, systems often can be estimated and used successfully in applications, there are cases where special attention is needed. A simple example of such a case is the following static nonlinear system

$$y(t) = y_l(t) + 0.01y_n(t) \tag{3.2a}$$

$$y_l(t) = u(t) \tag{3.2b}$$

$$y_n(t) = u(t)^3 \tag{3.2c}$$

with the input

$$u(t) = e(t) - 1.980e(t-1) + 0.9801e(t-2)$$

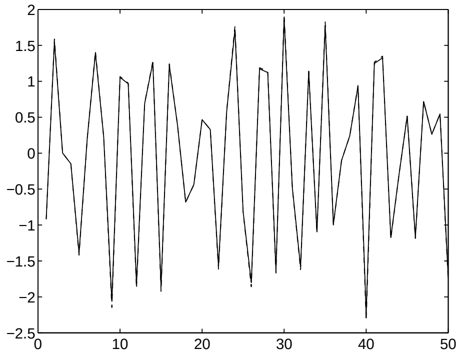
where $e(t)$ is a white noise process with uniform distribution over the interval $[-1, 1]$. For this bounded input, the output $y(t)$ will be very similar to $y_l(t)$, i.e., the output if the nonlinearity is removed. This can be seen in Figure 3.1(a) for a particular realization of the input signal.

However, the small differences between these output signals will give rise to totally different LTI-SOE:s. It is shown in [6] that the output error LTI-SOE (OE-LTI-SOE), i.e., the mean-square error optimal output error model, of the system (3.2) is

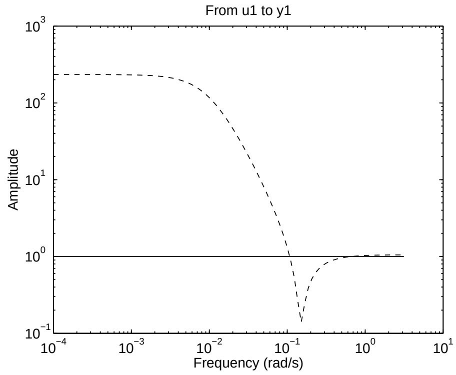
$$G_{0,OE}(z) = \frac{1.055 - 2.065z^{-1} + 1.034z^{-2}}{1 - 1.980z^{-1} + 0.9801z^{-2}}$$

and that it thus is far from the linear part $G_l(z) = 1$ of the system (3.2). The large differences between the frequency responses of these systems are shown in Figure 3.1(b). Since the OE-LTI-SOE is so far from the linear part of this almost linear system, this particular LTI approximation is probably not so useful for, for example, robust controller design. Notice that the OE-LTI-SOE of the static nonlinear system (3.2) is non-static, i.e., that it contains extra dynamics.

It can be shown that the sensitivity to small nonlinearities can be reduced if the input signal has a spectral density function that never is close to zero or if the input is Gaussian. Furthermore, Gaussian inputs have the property



(a) The output $y(t)$ (dashed) of the nonlinear system (3.2) cannot be distinguished from the output $y_l(t) = u(t)$ (solid) of the linear part of that system for a particular realization of the input signal.



(b) Bode plot showing the difference between the OE-LTI-SOE $|G_{0,OE}(e^{i\omega})|$ (dashed) and the linear part $|G_l(e^{i\omega})| = 1$ (solid) of the system (3.2).

Figure 3.1: The frequency response of the OE-LTI-SOE can be far from the response of the linear part of the system also when the nonlinear contributions to the output are small.

that they give rise to LTI-SOE:s without extra dynamics. Hence, for a Gaussian input, the LTI-SOE of a nonlinear finite impulse response (FIR) system will always be a linear FIR model. This property is useful for structure identification of nonlinear FIR systems and for identification of nonlinear systems that consist of an LTI system before or after a nonlinear FIR system. Most of the results about LTI-SOE:s for Gaussian inputs have also been published in [44].

Gaussian processes are separable and it turns out that separability of the input process is a both necessary and sufficient condition for the OE-LTI-SOE of an arbitrary nonlinear FIR system always to be a linear FIR model. Another property of Gaussian processes is that they always can be viewed as if they have been generated by filtering white noise through a minimum phase filter. Actually, if the input process is non-Gaussian, it is rather important that it is generated by filtering white noise through a minimum phase filter. For example, spectral analysis, which is a standard validation method, will not work otherwise.

3.5 Time-Delay Estimation

Svante Björklund's licentiate thesis, [9] deals with an overview and evaluation of different methods to estimate time delays (dead-times) in dynamical systems. See also [58] for a short conference presentation of the basic results.

Classification of methods

Most methods that have been suggested for time-delay estimation (both in control and signal processing) can be put into one of the following classes:

1. *Time-delay approximation model methods.* The input and output signals are represented in a certain basis and the time-delay is estimated from an approximation of the relation (a model) between the signals in this basis. The time-delay is not an explicit parameter in the model. Depending on the basis there are several subclasses:

   (a) *Time domain approximation methods.* The time-delay is the delay for the impulse response to start. Finding the peak of the cross correlation between input and output, which is a common method, is in principle the same thing.

   (b) *Frequency domain approximation methods.* The time-delay is estimated from the phase of the time-delay $e^{-i\omega T_d}$.

   (c) *Laguerre domain approximation methods.* The time-delay is estimated from a relation between the input and output signals expressed in Laguerre functions. Also other bases for the signals are possible, e.g. Kautz functions.

   There are two independent steps in these methods: 1) Estimate the approximation model. 2) Estimate the time-delay from the model.

2. *Explicit time-delay parameter methods.* The time-delay is an explicit parameter in the model.

   (a) *One-step explicit methods.* The time-delay and the other model parameters are estimated simultaneously. Estimating several models, e.g. ARX models, with different time-delays and choosing the best is also of this subclass.

(b) *Two-step explicit methods.* Alternating between estimating the time-delay and the other parameters.

(c) *Sampling methods.* Utilizing the sampling process to derive an expression for the time-delay. For example, zero order hold (zoh) sampling of a system with subsample time-delays creates an extra zero.

3. *Area and moment methods.* These methods utilize relations between the time-delay and certain areas over or below the step response $s(t)$ and certain moments of the impulse response $h(t)$ (integrals of the type $\int t^n h(t)dt$). There are two independent steps: 1) Estimate the step or impulse response. 2) Estimate the time-delay from these responses.

4. Higher-order statistics (HOS) methods. Their main advantage is that noise with a symmetric probability distribution function, e.g. Gaussian, theoretically can be removed completely by HOS.

Simulation setup

The thesis [9] contains a detailed simulation study of many of the time-delay estimatioin methods, listed above. On of the results of the study is summarized in Figure 3.2 (see [58] for an explanation of all the acronyms). A factorial experiment (several factors varied simultaneously) with simulated signals in open loop was performed in MATLAB. The signal-to-noise ratio (SNR), measured at the system output, was either 1 or 100. For each factor level combination, 1024 trials or repetitions were conducted. The noise $n(t)$ was white and Gaussian. The sampling interval was $T_s = 1$. The used input signals had a length of 500 samples and were:

- White or narrowband (most energy between 10% and 30% of the Nyquist frequency) random binary input signals. These input signals are common in system identification if the input signal can be chosen freely.
- Step input signals in the form `[zeros(50,1);ones(150,1); -ones(150,1); zeros(150,1)]` (MATLAB code).

All systems were of the form $G_j(s) = e^{-9s} \cdot \bar{G}_j(s)$. $\bar{G}_1$ had poles -0.1 & -1, no zeros and DC gain 1 (a slow second order system). $\bar{G}_2$ had poles -1 & -10, no zeros and DC gain 1 (a fast second order system). $\bar{G}_5$ had poles

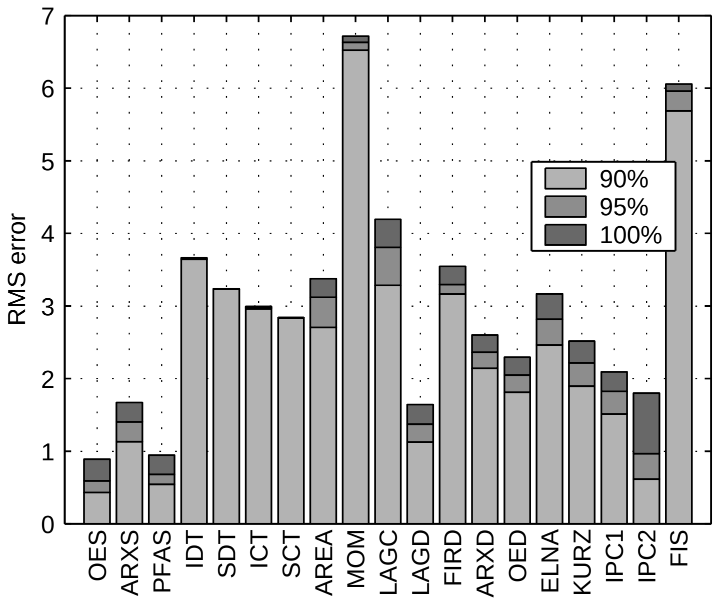


Figure 3.2: RMS error (in sampling intervals) for different methods when the 90%, 95% or 100% best estimates are retained. Average RMS error over SNRs, input signal types and systems. Maximum RMS error is 10. See [58] for definitions of the method names OES, ARXS, etc.

-0.1, -0.3, -0.6 & -1, zeros -0.4 & -0.9 and DC gain 1 (a fourth order system with real poles). $\bar{G}_6$ had poles $-0.1(1 \pm i)/\sqrt{2}$ & $-(1 \pm i)/\sqrt{2}$, zeros -0.4 & -0.9 and DC gain 1 (a fourth order system with complex poles). For all the systems the time delay was 10 after the (zero order hold) sampling.

3.6 Projection Techniques

Methods for Classification

In a broad variety of applications ranging from the information retrieval on the Internet to the processing of sensor signals, there is a constantly growing need to make use of patterns with very high dimensionality. One major task is of course the accurate *classification* of these patterns, but very important issues are also how to *compress* and how to *visualize* them. If numerical vectors represent the patterns, both these latter issues can be addressed by searching for special low-dimensional linear projections of the pattern vectors.

We usually assume every pattern is an observation of one of g populations. By *classification* we understand the task to infer which one of these populations a given pattern is an observation of. Usually, the pattern vector does *not* contain all information needed to make this inference fool proof. The uncertainties due to absent information will be manifested as noise that limits the possibility to distinguish between patterns from different populations. Given the probabilistic distribution of the noise, the *Bayes error* is a well-known definition for how confident the inference can be *at best*, despite the noise. No deterministic inference or classification rule can ever fall short of the uncertainty given by the Bayes error.

When pattern vectors are projected on a low-dimensional plane, valuable information is usually lost with an increase in noise magnitude and Bayes error as a consequence. This means it might not be possible to classify the low-dimensional representation of a pattern with the same confidence as allowed by the original pattern. Obviously, there is a whole set of k-dimensional projections in the original n-dimensional pattern space (we assume $k < n$). It is also rather obvious, that different projections in this set may result in different Bayes error. A natural and not very novel idea is to use the (particular) projection that gives the *lowest possible Bayes error*. However, it turns out that generally, this projection is very difficult to find. It is even difficult to compute the Bayes error for a given projection, and we are often resigned to use approximations.

In [130, 104] we address both the issue how to approximate the Bayes error in a projection, as well as how to find the projection where this approximation attain its minimum. We compare different numerical optimization techniques specialized for searching for optimal projections or *subspaces*. They are based on Givens rotations, Householder reflections, steepest descent and nonlinear conjugate gradients methods. The Bayes error approximations are based on the well-known Mahalanobis and Bhattacharyya distances, and the subspace gradients of these approximations are derived and used in the numerical optimization.

We conclude that among the methods studied in [130], the nonlinear conjugate gradients method is probably the best one to be used when searching for low-dimensional projections of pattern vectors.

In [113] we show how the Bayes error optimal one-dimensional projection of two concentric but heteroscedastic populations can be found by solving a generalized eigenvalue problem.

Methods for Dynamical Data

We consider the time-discrete SISO model

$$\begin{aligned} y_t &= f(\phi_t) + v_t \\ \phi_t &= \begin{bmatrix} y_{t-1} & y_{t-2} \cdots y_{t-n_a} & u_{t-n_k} & u_{t-1-n_k} \cdots u_{t-n_b-n_k} \end{bmatrix}^T \in \mathbb{R}^n \end{aligned} \tag{3.3}$$

with the special (multi-index) structure

$$f(\phi_t) = b^T \phi_t + g(S^T \phi_t). \tag{3.4}$$

Here, we think of g as the non-linear residual of the linear part b. We are particularly interested in how to estimate the low-dimensional projection S in $\mathbb{R}^{n \times k}$, and for this purpose, we can for instance use a simple polynomial fitter. In the case with $k = 1$ this polynomial is

$$g(x; c) = \begin{bmatrix} 1 & x^2 & x^3 \ldots x^{n_p} \end{bmatrix} c, \tag{3.5}$$

which is an ordinary polynomial minus the linear term. Once S is found, a more robust smoother can of course be used.

For sample data $\{y_t, u_t\}_1^N$ from *some* systems, the linear model residual $y_t - b^t \phi_t$ can be described very well in k dimensions, where $k < n$ or even $k = 1$. If S is estimated as a first step, the subsequent non-linear modeling can be greatly simplified. When $k = 1$ the problem is two-dimensional and can be visualized in a diagram with $S^T \phi_t$ on the horizontal axis and $y - b^T \phi$ on the vertical.

We aim to answer which criteria and which techniques to be used estimating the projection S.

3.7 ANOVA and Local Linear Models

A *Local Linear Model* can be described as a predictor that is linear in some regressors when the remaining regressors are fixed. The structure identification problem when estimating local linear models can be eased by using Analysis of Variance (ANOVA) as a prior step in the estimation procedure [45]. The information gained from using ANOVA on the input/output data is what regressors that should be used to partition the input space and what regressors are needed only for the linear models in each part. Also the complexity of the partitioning can be restricted due to the extra information.

In earlier work, it has been shown that the widely spread statistical analysis tool ANOVA can be used to extract structure information from input/output data. This can be done without estimating any complex model, which is a great benefit due to the complexity of the estimation task.

3.8 Parameter Estimation in Differential-Algebraic Equations

When a system is modeled using an object-oriented modeling tool like a Modelica environment, the equations describing the system form a differential-algebraic equation (DAE),

$$F(\dot{\xi}(t), \xi(t), u(t), \theta) = 0. \tag{3.6}$$

Here $x(t)$ is a vector of physical variables, $u(t)$ is an input signal and θ is a vector of (possibly unknown) constant parameters. If some parameters are unknown, it might be necessary to estimate them from input and output data. To be able to do this, we examine how unknown variables θ in a DAE can be estimated from input and output data.

During the year the case when the DAE is linear,

$$E(\theta)\dot{\xi}(t) = J(\theta)\xi(t) + K(\theta)u(t) \tag{3.7a}$$
$$y(t) = L(\theta)\xi(t), \tag{3.7b}$$

was examined [24]. Here, the problem can in principle be solved by transforming the system into state-space form. However, the internal variables $\xi(t)$ may depend on derivatives of $u(t)$, so the input might have to redefined as one of its derivatives to allow a transformation into state-space form.

Noise modeling is an important part of system identification, so it has also been examined how a noise model can be added to a linear DAE. Similarly to how noise is modeled in the case of state-space systems, a DAE with a noise model can be written as

$$E(\theta)\dot{\xi}(t) = J(\theta)\xi(t) + K_1(\theta)u(t) + K_2(\theta)v_1(t) \tag{3.8a}$$
$$y(t) = L(\theta)\xi(t) + v_2(t) \tag{3.8b}$$

where $v_1(t)$ and $v_2(t)$ are noise signals. If $v_1(t)$ is white noise, its derivative is not well defined. K_2 must be then be selected so that derivatives of $v_1(t)$ do not affect $\xi(t)$. This is discussed in [26].

3.9 Subspace Methods

So called *Subspace methods* have been the subject of considerable recent interest in the literature on System Identification. The methods are intriguing, since they are numerically efficient, fast and do not require iterative search. At the same time they contain several design variable choices, and there is no full understanding about the best choices of these. A simulation study of the effects of several of the most important design variables was carried out in [51].

Normally subspace algorithms are robust and reliable. An example where they give very bad estimates was investigated in [52]. The reasons were traced to general properties of ARX-estimates, and it was shown that focusing on lower frequencies could be a remedy.

Another fact with standard subspace methods is that they employ ARX estimates of models with unnecessarily many parameters in the first step. In [50] is was argued and shown that it would be advantageous from an accuracy point of view to use models with fewer parameters for this purpose. A related aspect is that subspace methods usually fail with closed loop data. A further modification that takes care of that problem is described in [46]. The idea is to make an estimate of the innovations sequence, in order to avoid the correlation between past innovations and the input.

3.10 Miscellaneous

Variance Expressions and Model reduction in System Identification

In earlier annual reports we have described work on how the variance of an estimated model is transformed and affected when the order of the estimated model is reduced. Some new results include variance expression for reduced output error models, [17], as well as analysis of a two-step ARX-procedure for model reduction, [11]

Models with Mixed Parametric and Nonparametric Uncertainty

In some cases, especially for control, it may be useful to characterize the error of the estimated model in both non-parametric and parametric terms. The paper [10] contains results in this direction. It also shows how these uncertainty measures can used in robust control.

Curve Fitting

Viewing parameter estimation as curve-fitting with least-squares techniques is a classical perspective with roots going back to Gauss and before. In fact, it gives a useful framework to view all linear dynamic model estimation as curve-fitting of the frequency response functions. Important insights are gained, especially for investigating local function fitting to multivariable frequency functions (essentially "spectral analysis"). This perspective is treated in [16].

Initialization of parametric search in identification of linear systems

When we have a physically parameterized linear model, it is important question to find good initial parameter estimates, where to start the iterative search for the best parameters. This is an essential problem in practice also for linear models, since random initialization of structured output-error models tend to end up in " wrong" local minima.

Since subspace identification methods are generically consistent, it is tempting idea to identify such a black-box model first and use this model to try to find good initial values in a physically parameterized one. The paper [48] describes how this can be done using a sum-of-squares formulation in combination with semidefinite programming.

Education and Software

Version 6 of the System Identification Toolbox is described in [47]. It has been extended to deal with simple process models like

$$y(t) = \frac{K}{1 + sT_p} e^{-sT_d} \tag{3.9}$$

and to handle frequency domain input-output data as well as frequency function data as observations.

Educational aspects of interfaces for Identification software tools are discussed in [49].

Chapter 4

Nonlinear Systems

4.1 Backstepping for rigid bodies and flight control

Backstepping is a Lyapunov based nonlinear control design method that provides an alternative to feedback linearization. In [4] backstepping is used to derive robust linear control laws for two nonlinear systems, related to angle of attack control and flight path angle control, respectively. The resulting control laws require less modeling information than corresponding designs based on feedback linearization, and achieve global stability in cases where feedback linearization can only be performed locally. Further, a method for backstepping control of a rigid body is developed, based on a vector description of the dynamics. It is also discussed how to augment an existing nonlinear controller to suppress constant input disturbances. Two methods, based on adaptive backstepping and nonlinear observer design, are proposed.

4.2 Control allocation

Control allocation deals with actuator utilization for overactuated systems. In [4] the control allocation problem is posed as a constrained least squares problem to account for actuator position and rate constraints. Efficient solvers based on active set methods are developed with similar complexity to existing, approximate, pseudoinverse methods. A method for dynamic control allocation is also proposed which enables a frequency dependent control distribution among the actuators to be designed. Further, the relationship between control allocation and linear quadratic control is investigated in [38]. It is shown that under certain circumstances, the two techniques give the same freedom in distributing the control effort among the actuators. An advantage of control allocation, however, is that since the actuator constraints are considered, the control capabilities of the actuator suite can be fully exploited.

4.3 Model Predictive Control

Controlling a system with control and state constraints is one of the most important problems in control theory, but also one of the most challenging. Another important but just as demanding topic is robustness against uncertainties in a controlled system. One of the most successful approaches, both in theory and practice, to control constrained systems is model predictive control (MPC). The basic idea in MPC is to repeatedly solve optimization problems on-line to nd an optimal input to the controlled system. In recent years, much effort has been spent to incorporate the robustness problem into this framework. The main part of [1] revolves around minimax formulations of MPC for uncertain constrained linear discrete-time systems. A minimax strategy in MPC means that worst-case performance with respect to uncertainties is optimized. Unfortunately, many minimax MPC formulations yield intractable optimization problems with exponential complexity. Minimax algorithms for a number of uncertainty models are derived. These include systems with bounded external additive disturbances, systems with uncertain gain, and systems described with linear fractional transformations. The central theme in the different algorithms is semidefinite relaxations. This means that the minimax problems are written as uncertain semidefinite programs, and then conservatively approximated using robust optimization theory. The result is an optimization problem with polynomial complexity. The use of semidefinite relaxations enables a framework that allows extensions of the basic algorithms, such as joint minimax control and estimation, and approximation of closed-loop minimax MPC using a convex programming framework. Additional topics include development of an efficient optimization algorithm to solve the resulting semidefinite programs and connections between deterministic minimax MPC and stochastic risk-sensitive control. In [1] also stability issues in MPC for continuous-time nonlinear unconstrained systems are treated. While stability of MPC for unconstrained linear systems essentially is solved with the linear quadratic controller, no such simple solution exists in the nonlinear case. It is shown how tools from modern nonlinear control theory can be used to synthesize finite horizon MPC controllers with guaranteed stability, and more importantly, how some of the technical assumptions in the literature can be dispensed with by using a slightly more complex controller.

A problem with minimax MPC is that the controller can become overly conservative. An extension to minimax MPC that can resolve this problem is closed-loop minimax MPC. Unfortunately, closed-loop minimax MPC is essentially an intractable problem. In [56], a novel approach is introduced to approximate the solution of a number of closed-loop minimax MPC problems. The result is convex optimization problems with size growing polynomially in system dimension and prediction horizon.

4.4 DAE models

General approaches to modeling, for instance using object-oriented software, lead to differential algebraic equations (DAE), also called implicit systems. For state estimation using observed system inputs and outputs in a stochastic framework similar to Kalman filtering, one needs to augment the DAE with stochastic disturbances (process noise), whose covariance matrix becomes the tuning parameter. In [26] the subspace of possible causal disturbances based on the linear DAE model is determined. This subspace determines all degrees of freedom in the filter design, and a Kalman filter algorithm is given. This is illustrated in the design of a filter for a system with two interconnected rotating masses.

In [24] it is described how parameter estimation can be performed in linear DAE systems. Both time domain and frequency domain identification is examined. The results are exemplified on a small system. A potential application for the algorithms is to make parameter estimation in models generated by a modeling language like Modelica. Using noise models in identification of DAEs leads to potential problems beacause of possible impicit differentiation of the white noise. How this is avoided is described in [26].

4.5 Algebraic Methods in Control

In [117] the application of identifiability criteria to mean- value models of turbocharged IC enginesis treated. A way of reducing such models to linear regressions using differential algebra is presented. The conditions of global identi ability and persistent excitation are formulated in explicit form for a given set of sensors. It is accompanied with a technique for reducing the set of sensors required for the engine identification. The software tools required are outlined and their complexity is discussed.

Chapter 5

Sensor fusion

This project is carried out by Division of Communication Systems and Division of Automatic Control in cooperation with SAAB (Dynamics and Gripen) Volvo (Cars), and NIRA (Automotive algorithms). Highlights of the year are

- The PhD thesis by Jonas Elbornsson [3].
- The licentiate theses by Thomas Schön [5], Erik Geijer Lundin [7] and Frida Gunnarsson [8].

The students in this area are summarized below:

Name	Company	Funding	Start	Lic.	PhD
Jan Palmqvist	SAAB Aircraft	ISIS	1995	1997	–
Niclas Bergman	–	ISIS	1996	1997	1999
Jonas Elbornsson	–	ECSEL	1999	2001	2003
Rickard Karlsson	formerly SAAB Dyn.	ISIS	2000	2002	–
Per-Johan Nordlund	SAAB Aircraft	ISIS	2000	2002	–
Jonas Jansson	Volvo Car	Volvo	1999	2001	–
Andreas Eidehall	Volvo Car	Volvo	2002	–	–
Christina Grönwall	FOI	FOI	1997	2000	–
Frida Gunnarsson	–	ECSEL	2000	2003	–
Gustaf Hendeby	–	ISIS	2002	–	–

Jan Palmqvist became manager of the navigation group at SAAB 1998, a position that Per-Johan Nordlund was offered 2002. Niclas Persson became a project leader at NIRA Dynamics 2002. Niclas Bergman is now at SAAB

CelsiusTech and he is responsible for data fusion within the SAAB concern. Jonas Elbornsson started at MathCore AB during 2003.

5.1 Overview

We will here describe the general area of sensor informatics illustrated with previous highlights in research.

Motion dynamics	$x(t_{k+1}) = f(x(t_k), w(t_k))$	$\approx$	$x(t_{k+1}) = Ax(t_k) + w(t_k)$
Sensors: IS, GIS, Vision	$y(t_k) = h(x(t_k), e(t_k))$	$\approx$	$y(t_k) = Cx(t_k) + e(t_k)$
Filter	Approximate PF $\Rightarrow \hat{x}^{PF}$		"Exact" KF $\Rightarrow \hat{x}^{KF}$

Table 5.1: *Overview of a sensor fusion system with possible filtering approaches. The sensor delivers measurements $y(t_k)$ with time stamps t_k, which may come irregular in time and with jitter noise. This is the subject of Section 5.4. For almost linear models and Gaussian shaped noise, $\hat{x}^{KF}$ should be prefered, while for non-linear models or sensors with non-Gaussian error distributions should at least be $\hat{x}^{PF}$. The theoretical best choice and computational aspects are the subjects of Section 5.3.*

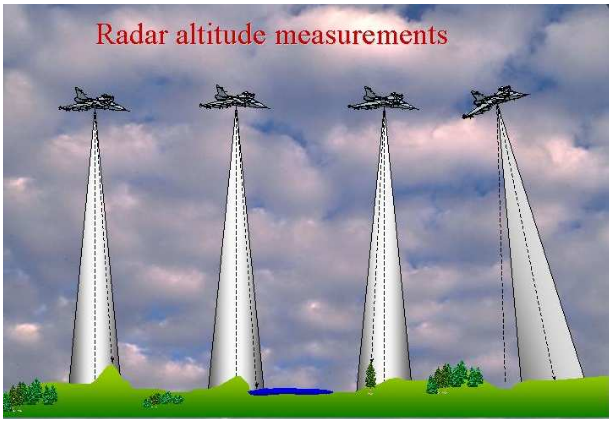
width=8cm 

Figure 5.1: *The second generation terrain navigation system in Gripen (Saab AB) is based on approximate Bayesian non-linear filtering using terrain variation as the primary information. We are working on a particle filter based solution for terrain positioning* and *integrated navigation for the third generation system.*

We split the *sensor informatic problem* into

- high-level sensor fusion and
- low-level sensor sampling problem.

The reason for the latter is that is turns out to be a fundamental sensor fusion problem that must be solved when the data is not uniformly sampled or, due to bus communciation problems for instance, a sampling jitter is present.

The general problem of utilizing all available sensor information is called sensor fusion. Mostly, one assumes that the sensor measurements are related by a dynamic model, and we face a filtering problem. The optimal solution given by Bayes' law is well-known. In case the dynamic model is linear, the Kalman filter theory applies. In the non-linear case, several numerical approximations have appeared in the past, though quite few applications of these have been reported. It was first with the invention of the particle filter by Gordon *et.al* in 2003 that a general working solution with a sound theoretical basis that the signal processing community started to apply approximate non-linear filtering to real-world problems. During the past five years, many applications have been reported, and the theory has made substantial progress. Table 5.1 summarizes the sensor fusion model and the two choices of linear or non-linear filtering.

Pre-processing of sensor signals is in many cases decisive for the sensor fusion performance. We have found that for several inertial navigation problems, non-uniform sampling is in particular critical. In Table 5.1, non-uniform sampling is illustrated as explicit time stamps t_k attached to each measurement. In a model-based filtering framework, this does not pose a problem in itself. The main problems are random errors on t_k and deterministic jitter (cyclic unknown error) in t_k. Non-uniform sampling is a relatively unexplored area in signal processing where few hard facts are available.

5.2 Sensor fusion – our past activities

The group started its sensor fusion activities 1996 within the Vinnova competence center ISIS. Figure 5.3 summarizes the projects, students, achieved exams and their relations. Here, the names at the corners are industrial students recruited from SAAB Gripen, SAAB Dynamics, Volvo, NIRA Dynamics and FOI. The names in the center of Figure 5.3 have had a central role in developing the theoretical edge of the group in the area of particle filtering for sensor fusion, where Thomas Schön is currently funded by VR.

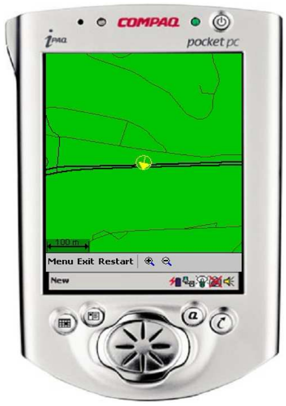


Figure 5.2: *The car navigation system MAP (NIRA Dynamics AB) is based on particle filtering using wheel speeds and street map as only information.*

Initially, the initiatives to all of our projects came from industry: Volvo for collision avoidance, FOI for object identification, SAAB Gripen for integrated navigation and SAAB Dynamics for terrain navigation, see Figure 5.1. Later on, our own work led to new ideas of possible applications, where we mention car navigation (NIRA Dynamics), underwater navigation (SAAB Dynamics) and surface (ship) navigation (FOR Shore). We made internal feasability studies and developed taylored theory, then handed over complete project proposals to the companies, where car navigation already is a commercial product, see Figure 5.2. Starting with (extended) Kalman filter approaches to

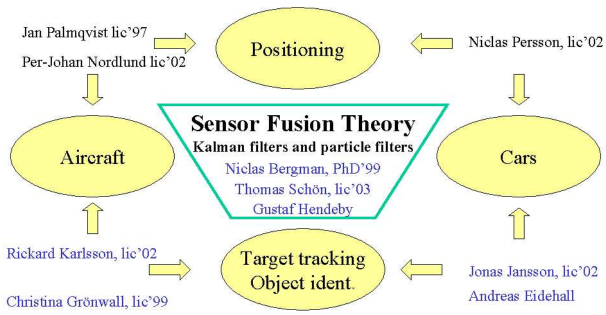


Figure 5.3: *Previous research projects in sensor fusion*

navigation and target tracking, it was quite soon found that several problems cannot be satisfactorily solved with linearized dynamic models and Kalman filters. That was the reason for an early introduction of particle filters to the group.

5.3 Sensor fusion – projects

The current projects include

- Particle filters for system identification, see [30] and [22] for the invitated session at SYSID'03. A wellknown general approach to system identification is to put the model structure on state space form, and extend the state vector with the parameters to be identified. The interesting question is how well the particle filter performs on such models, and it is not trivial to answer the question since the augmented state vector does not lead to an ergodic process which is one requirement for the particle filter theory. For linear model structures, this approach leads to a bilinear state space model, and then an important practical question is how to marginalize the state vector to get a lower-dimensional state vector. This is the subject of [22]. For instance, marginalizing the parameters avoids the problem of ergodicity mentioned above.

- The relation between optimal filtering and convex optimization is treated in [20]. The Kalman filter can be derived using a convex optimization framework, and this leads to that a more general class of filtering problems can be solved with standard software. For instance. inequalities and constraints on the state vector can be included in the model.

- Underwater navigation using terrain databases is presented in [34]. Basically, the problem and solution is the same as for aircraft terrain navigation, see Figure 5.1. The contribution here is a dedicated analysis and algorithm, with intuitive Cramer-Rao bound expressions for how good the performance might be.

- Positioning of cellular phones is investigated in [33]. In particular, time difference of arrival (TDOA) measurements promise good positioning in current and future standards. We have derived maximum likelihood estimators and particle filters for this problem.

- Particle filters for differential algebraic equations pose a quite specific problem as described in [26]. Basically, DAE:s appear from physical modeling, and in this context no process noise is usually included.

However, for filtering by for instance the particle filter, certain process noise is needed for model errors, actuator noise and roughening of the filter. What is specific with DAE:s is that noise in certain subspaces correspond to non-causality, and the contribution is a contrutive way to determine in what subspace the state noise may reside.

- Cramer-Rao analysis in laser radar imaging systems is presented in [59].

5.4 Sensor informatics

Our previous experience is summarized in Figure 5.4. Non-uniform sampling naturally occurs in the following cases

- Event-based sampling as for instance the angular measurements that are done on rotating shafts. This occurs in the drive line and at the wheels ("ABS sensors") in vehicles and in robot arms, for instance. That means that the sensor delivers time instants t_k for a uniform angle grid $2\pi k/N$. Due to imperfect angle sensors, a regular jitter (offset to t_k) occurs. This jitter should be eliminated close to the sensor, since the error is hard or even impossible to estimate in (time-domain) sensor fusion.

- Using parallel computations for high-speed applications, as the project on parallel AD Converter structures of Jonas Elbornsson in Figure 5.4, a jitter effect occurs due to lack of exact synchronization of the computation blocks. That means, that the sampling times have a cyclic and unknown offset added to them.

- Stochastic sampling jitter occurs when time stamps of sensor measurements have unknown random errors. This occur for instance in some communication protocols as CAN in vehicles and in high-speed applications where clock synchronization in not perfect.

Quite interestingly, both angular sampling and parallel computations lead to the same cyclic jitter. Partial results of how to estimate the jitter, and reconstruct a uniformly sampled signal appeared in [3] and [32]. A very preliminary investigation of stochastic jitter was presented in [8] and [19].

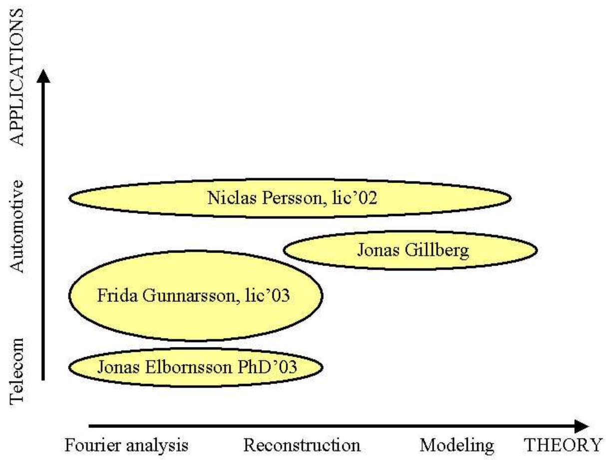


Figure 5.4: Previous research projects in non-uniform sampling

Chapter 6

Detection and Diagnosis

6.1 Fault Isolation in Control Systems with Object Oriented Architecture

Introduction

Developing control systems for complex systems is a difficult and increasingly important task. Large control systems have traditionally been developed using structured analysis and functional decomposition. Today, many large systems are designed using an object oriented approach. This has several advantages over traditional approaches, including better possibility to cope with complexity and to facilitate maintenance and reuse. It leads to new kinds of problems, though, and we concern ourselves with the problem of fault propagation caused by an object oriented software architecture. As basic inspiration and case study we have used a commercial control system for industrial robots developed by ABB Robotics; the system is highly configurable, programmable and has an object oriented architecture. More work on industrial robots is described in Chapter 8.

Object-oriented design goals such as *encapsulation* and *modularity* often stand in direct conflict with the need to generate concise information about a fault situation, and to avoid propagating error messages. Error messages are sent by individual objects to notify, e.g., an operator that an error condition has been detected. The aim to encapsulate information implies that individual objects, or groups of objects, in general do not know how close they are to the fault or if the fault has already been adequately reported by another part of the system. When a fault situation occurs, e.g, a hardware component failure, a broken communication link or a real-time fault, it is not a very desirable system behavior to present a multitude of error messages from different parts of the system to an operator. For the operator, who normally has no insight in the internal design of the control system, it can be very difficult to understand which error message that is most relevant and closest to the real fault. For objects that are close to each other it is possible to suppress error messages by information passing, but this is not always feasible.

There are two main objectives of our work: On the one hand we want to devise a method that can be used for operator support. The aim is then to single out the error message that explains the actual cause of the failure, or possibly an unobservable critical event explaining the observations. We aim to discard error messages which are definitely effects of other error messages, while trying to *isolate* error messages (or critical events) which explain all other messages. That is, we propose a fault handling scheme as an extra layer between the operator and the core control system, performing post-processing of the fault information from the system to achieve clear and concise fault information to the operator, without violating encapsulation and modularity. On the other hand, our method can also be used at design time. At the design level, we want to find out, at design-time, if the error log design is sufficient, that is, if enough error messages are produced to be able to isolate all faults.

The fault isolation is done in two steps. In the first phase a structural model fault isolation is done, and in a second phase a behavioral model fault isolation is used only if needed. If the structural model fault isolation is successful in finding a single cause of all the error messages, the second phase of behavioral model fault isolation is not needed.

The structural model is represented mainly by the class diagrams in UML (unified Modeling Language). The main advantage with using a software engineering model is that it can be developed and maintained at a relatively low cost as it is an integrated part of the software development process. From the error messages in the error log we can find the cause-effect relation between the error messages. If there is no unique maximal element initially, we use the UML model, in particular the class diagrams, to extend the original graph. A prototype implementation of the structural approach has been made and tested on the ABB Robotics industrial robot control system.

Behavioral fault isolation

Since the structural model thus is an abstraction of all possible behaviors, it is not unlikely to have circular dependencies in the structural model without ever having circular dependencies in any specific scenario. When such a circular dependency occurs in the explanation graph the structural model is not sufficient to perform successful fault isolation, but having a behavioral model of the objects involved in the cycle we may be able to break the cycle. A dependency in the structural model, say class A depends on class B, means that there exists a scenario where an instance of class A depends on an instance of class B. It is not possible to deduce whether the dependency holds in the scenario at hand or not, since the model does not discriminate between different scenarios. By modeling also the behavior of the objects we get the opportunity to reason about dependencies that hold only under certain circumstances, i.e. in certain scenarios.

When starting behavioral model fault isolation we have a limited set of root candidates, i.e. events in the scenario that are suspected to have caused the failure of the system. This set is an output from the structural model fault isolation.

Our main focus lately has been to extend the structural approach to fault isolation using *behavioral methods* -more precisely we use UML state machines as notation for the behavioral model- and class instances rather than classes. We use the concept of *strong root candidate*. A strong root candidate is an event that is known to have occurred, and there is a run (consistent with the log) where this event is the first critical event.

We propose an approach to fault isolation based on *model checking* to locate strong root candidates (if they exist!). The property of being a strong root candidate is then expressed in the temporal logic CTL (normally used for verification). And we use an existing model checker to single out the strong root candidates. However, a main obstacle in model checking is the so-called state-space explosion–the number of global system states typically increases exponentially with the number of subsystems. Techniques have been proposed to stretch the limits of model checking (e.g. symbolic model checking and partial order reduction). However, in our case we do not solve a general model checking problem but a more specific problem. Consequently there are more efficient abstraction mechanisms for our particular problem, and we propose such a method in [111, 43, 57]. The general idea is that we are only interested in the correlation between the first critical event and the set of messages that are logged during the execution. Hence, we can abstract away details not only about parallel object interleavings as in partial order reduction, but also ignore order of messages and dynamics that in the global system model does not change the set of messages sent or the order of critical events. For example, cyclic behavior where no critical events occur can be abstracted to a single state. Before applying model checking we perform abstraction, thus reducing the state space considerably and facilitating checking of the strong root candidates using model checking.

The result produced by our method is a table that maps all possible message logs to the corresponding strong root candidates. The table, called the fault isolation table, can of course be used for fault isolation; given a log and the fault isolation table, the strong root candidates can be found simply by table lookup. The primary use is in diagnosability analysis, though. The table partitions all possible system runs in equivalence classes of runs with the same logged messages. Each partition corresponds to a row in the table. If for such a row, there are several strong root candidates, we conclude that runs in the corresponding class are not diagnosable. If an error message is redundant, it will be evident from the table. If it depends on some other message, the two will only appear in certain configurations in consistent logs. The exponential size of the table indicates that it is not feasible to use it explicitly in general for systems with a large set of logged events. Then, abstractions of the table can be considered and presented to a user, for example the set of table rows that indicate non-diagnosability.

We have developed a prototype tool, StateTracer, that takes a description of a system as input and produces a fault isolation table as output along with visualizations of all merged objects. The system description is given in UML.

6.2 Fault detection and diagnosis in process control systems

This project is carried out by in cooperation with ABB Automation Systems and ABB Corporate Research. The aim is to study and develop methods for detection and diagnosis in process control applications.

This project focuses on fault detection and diagnosis in pulp and paper processes. Typical characteristics of these systems are that they are large systems with a large number of signals/sensors, and the physical models are of limited accuracy.

We investigate how to make a model of a system with a large number of signals, where furthermore only a small part of the signal space contains data under normal operations. PCA, principal component analysis is a promising method for this, where singular value decomposition is used to find the relevant parts of the signal space. The PCA model can then be used to compare measured process output with model output, and compute a test statistic, which will differ from zero when a fault has occurred.

Once a fault is detected, the next step in the fault detection and diagnosis is to find the faulty sensor. Using a probabilistic approach we can minimize the misclassification.

PCA has usually been employed for static systems, and for certain sampling rates, the pulp and paper process can be regarded as such. It is however also interesting to include dynamic information into the model, i.e., by including delayed versions of the signals in the regressor. This is known as dynamic PCA, dPCA, and closely related to subspace methods.

Another approach to fault detection is the parity space approach which is an elegant and general tool for additive faults in linear systems and is based on intuitively simple algebraic projections and geometry. It provides a tool to compute a residual vector that is zero when there is no fault in the system and reacts to different faults in different patterns, enabling a simple algorithm for diagnosis (deciding which fault actually occurred). Examples on simulated data often show very good results. A main drawback is that the approach does not take measurement errors and state noise into consideration as in the classical Kalman filter literature.

We mix the linear state space models used in fault detection and Kalman filtering, treating deterministic and stochastic disturbances in different ways.

In [31] a comparison is made between the parity space analyzed in a stochastic setting and PCA. The result is thaty PCA has similar fault detection and isolation capabilities as the stochastic parity space approach.

Chapter 7

Communication Applications

7.1 Introduction

The global communications system today (the telephone system yesterday) is considered as the largest man-made system all categories. Due to the dramatic increase in number of users and their demand for more advanced services, the available resources have to be utilized efficiently. This is especially critical in the subset of wireless cellular communications systems, and in applications which require specific real-time behavior. The four projects are rather independent, but can to some extent all be related to the exemplifying wireless network in Figure 7.1.

Signal Processing for Analog to Digital Converters (ADC) With adequate signal processing, it is possible to significantly improve analog to digital converters. This is important for cheaper and more accurate radio receivers and to effectivice the individual links.

Power Control in Cellular Radio Systems Power control is an important means to compensate for variations in propagation conditions and interference and to utilize the radio resources efficiently. Thereby, sufficient power is used by each transmitter to maintain an acceptable quality of service, while not disturbing other connections unnecessarily much. Both control design and analysis aspects are considered of such distributed algorithms.

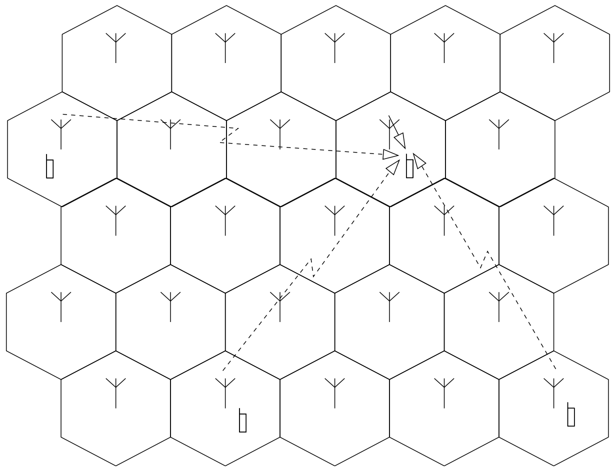


Figure 7.1: Downlink communications in a wireless network. The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

Uplink Load Estimation and Management Power control is not an efficient means for resource utilization if the system is overloaded. Therefore, it is important to manage the system load. Uplink load estimation is central due to the limited availability of accurate measurements. Furthermore, admission, congestion and other resource control are important tools to prevent the system from becoming overloaded.

Control, Fault Detection and Estimation in Data Networks Traffic flow control is well established in data communications. With mobile Internet becoming increasingly popular, it is important to consider these algorithms while cater for efficient utilization of the wireless links. Considered performance aspects are similar when discussing solely wired communications.

7.2 Signal Processing for Analog to Digital Converters (ADC)

Much of the physical space and power consumption in modern communication systems such as ADSL modems, cellular phones and radio base stations are due to the radio frequency signal processing. A very fast A/D converter could, in principle, be put directly to the antenna or at least closer to the antenna than today, and much more of the signal processing could be performed in software. This requires A/D converters with very high linearity to distinguish a weak signal from the harmonics from stronger signals.

Blind Equalization of Static Errors in SA-ADC and pipelined ADC

For fast high performance A/D conversion, pipelined or subranged successive approximation A/D converters (SA-ADC) are the best options. These A/D converters consist basically of a resistance ladder, where the voltage level between the resistances gives the digital reference levels. The correct digital level is found by comparing the analog input signal to these reference voltages, by binary search. Using only one resistance ladder, 2^N resistances are required to achieve N bits precision in the ADC. Pipelining or subranging is used to avoid too long resistance ladders. For these types of ADCs the comparison is split into two or more resistance ladders. The most significant bits are found from the first resistance ladder. When the correct level is found in the first ladder, another resistance ladder is fit into the correct interval in the first ladder, where the search is continued and less significant bits are found. In Figure 7.2 an example of a two stage subranging SA-ADC is shown. To

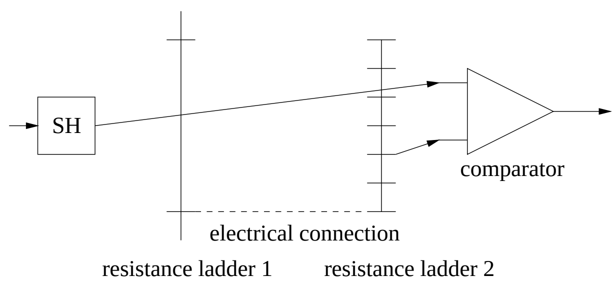


Figure 7.2: Two stage subranging SA-ADC. The conversion is done in two steps with two resistance ladders.

keep the power consumption and price at low levels, CMOS technology is used. One major problem is manufacturing errors leading to large uncertainties in the components. Due to errors in the resistances the distance between different reference levels in the resistance ladder are different, which means that the nominal digital reference levels do not correspond to the actual levels in the A/D converter. If the correct levels are known, these can be used to construct the digital signal instead of the nominal, equally spaced, reference levels. Here we have developed a patented method to adaptively and blindly compensate for the distortion with an algorithm suitable for implementation on the chip. We need only a spatial smoothness assumption on the input signal for this algorithm to work.

Adaptive Estimation of Amplitude, Gain and Timing Offsets in Parallel ADC's

One way of improving the speed of A/D conversion is to put M A/D converters in parallel. All the A/D converters have the same input signal but the clock signal is delayed with iT/M, where T is the sampling interval of one ADC. The outputs are then multiplexed to one signal with M times higher sample rate than the separate ADCs, see Figure 7.3. Due to this parallel,

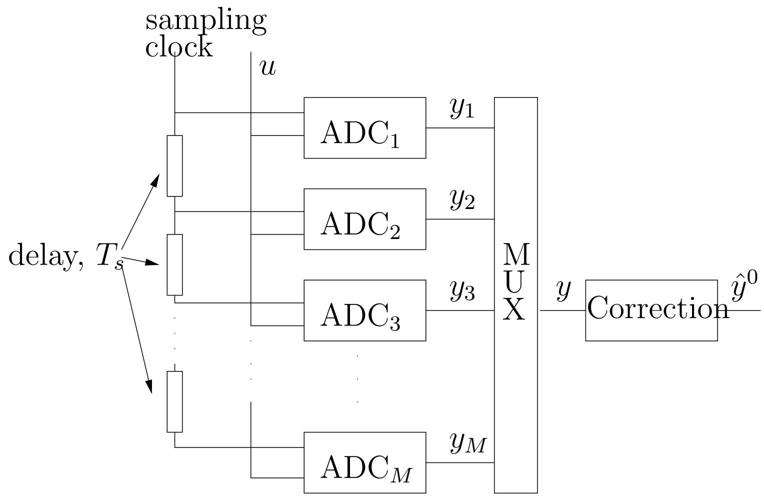


Figure 7.3: M parallel ADCs with the same master clock.

time interleaved setup, three types of errors occur:

- **Time errors (static jitter)**
  The delay time of the clock to the different A/D converters is not equal.

This means that the signal will be periodically but non-uniformly sampled.

- **Amplitude offset errors**
  The ground level can be slightly different in the different A/D converters. This means that there is a constant amplitude offset in each A/D converter.

- **Gain error**
  The gain, from analog input to digital output, can be different for the different A/D converters.

Here it is of utmost importance to compensate for gain, amplitude and time offsets, otherwise fake components in the frequency spectrum will appear. Here a patented blind adaptive algorithm for estimation of time errors has been developed. The algorithm requires no information about the input signal, except temporal smoothness.

Randomly interleaved ADCs

Another way to decrease the impact of mismatch errors in time interleaved ADCs is to randomize the selection order of the ADCs. By doing this the mismatch errors give a more noise-like shape in the output spectrum. This means that the SFDR is improved while the SNDR is the same. A statistical model for this type of system has been developed. This model has also been compared to measurements from a real randomly interleaved ADC system. For further analysis, see [32].

Jonas Elbornsson and Fredrik Gustafsson are working in this project, see also the project description.

7.3 Power Control in Cellular Radio Systems

When a user is requesting a service from the cellular system, a radio link has to be established. First the appropriate base station to connect to is determined. The requested service corresponds to a specific data rate, and therefore a channel that can provided this data rate is allocated. Most things in the system are time-varying: mobiles move, users come and go, propagation condition varies etc. Closed-loop transmission power control is widely discussed as a means to compensate for the variations.

Since several connections are using the same channel, a signal intended for a certain user will reach other users as well, see Figure 7.1. This creates mutual interfering signals between the users and limit the performance.

For practical reasons, the powers have to be computed locally for each connection using local feedback, though performance and stability depend on how the different connections interact. We consider the power control problem as a decentralized control system, consisting of interconnected local control loops. Each connection controls the powers to obtain a sufficient *signal-to-interference ratio (SIR)* γ, which is the useful received power C divided by the harmful power, or interference power I (including thermal noise). In dB, SIR $\gamma_{dB} = C_{dB} - I_{dB}$. The reference values, typically referred to as target SIR:s, are denoted by γ^t. Hence, the challenge is to locally control the transmission powers using feedback of the control error $\gamma^t - \gamma_{dB}(t)$ to maintain an acceptable perceived connection quality.

Properties like stability and convergence are typical global properties related to the overall wireless network with mutual interference between the connections. While it is desirable to design and use the controllers locally, global stability results also have to be provided. It is easy to conclude that local stability is a necessary but not sufficient condition for global stability of the power control problem.

By analyzing power control from a control theory perspective, the following limitations are important:

- Not every user requirements can be supported by the system in terms of data rate.
- In practical cases the power can only be controlled based on local measurements and estimates.
- Measuring, estimation and control signaling takes time, which result in time delays in the system. Essentially, there is a trade-off between estimation accuracy and the presence of time delays.
- The measurements and/or control signals have to be transmitted over the radio interface. Since the available radio resources are limited, so is the feedback bandwidth. Moreover, the feedback channel may be subject to signaling errors resulting in feedback errors.
- The output power levels are limited to a given set of values due to hardware constraints. This includes quantization and saturation.

- The ability to mitigate time-varying disturbances are most naturally discussed in the frequency domain. An interesting issue is to address the performance in terms of the disturbance rejection bandwidth.
- 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.

These aspects are further discussed in the survey article [15].

Macro diversity is an important feature of WCDMA, where users can be connected to several base stations simultaneously. Then, the transmission power is adjusted to ensure than at least one link is received with acceptable quality. In practical uplink situation, this means that the mobile adjusts its power according to the base station which require the lowest power. Since the feedback communication is volatile and subject to errors, such a strategy may result in bad quality or even dropped calls. Instead, the feedback link quality should be considered when deciding what feedback commands that are reliable [37].

Dedicated links in WCDMA are power controlled to ensure quality of service. The link quality also depend on the channel estimation performance. This is related to the received quality of the Common Pilot Channel (CPICH), which is used for channel estimation. Furthermore, mobile meaurements of CPICH quality are reported to the network to support handover functionality, when determining the most appropriate base stations to connect or transfer to. In a planning stage, the cell sizes can therefore be adjusted by using different CPICH power levels in different cells. Such load sharing can adapt the cell coverage to a predicted traffic density to optimize the capacity of the wireless network [36].

Fredrik Gunnarsson is working on the project, which is a collaboration with Ericsson Radio Systems, Linköping and Kista.

7.4 Uplink Load Estimation and Management

When operating a cellular radio system at nearly full capacity, admitting yet another user may jeopardize the stability of the system as well as the performance of the individual users. Therefore, proper radio resource management is crucial. It is natural to base such management on a measure of the current load situation. This project aims at methods for estimating and managing the uplink load.

Prior art includes measures related to absolute number of users served by the base station and measures of the total received power at the base station I_j^{tot}. Both show promising results, but the former is difficult to configure, and the latter is based on a quantity, which is hard to measure accurately. Instead, the relative load of a base station is defined by

$$L_j = 1 - \frac{N_j}{I_j^{tot}} \Longleftrightarrow I_j^{tot} = \frac{N_j}{1 - L_j} \tag{7.1}$$

where N_j is the thermal noise power. Clearly, the relative load $L_j = 0$ corresponds to an unloaded base station (the received power is only thermal noise). Furthermore $L_j = 1$ constitutes an upper limit since it corresponds to an infinite received power, see Figure 7.4. An alternative definition of uplink

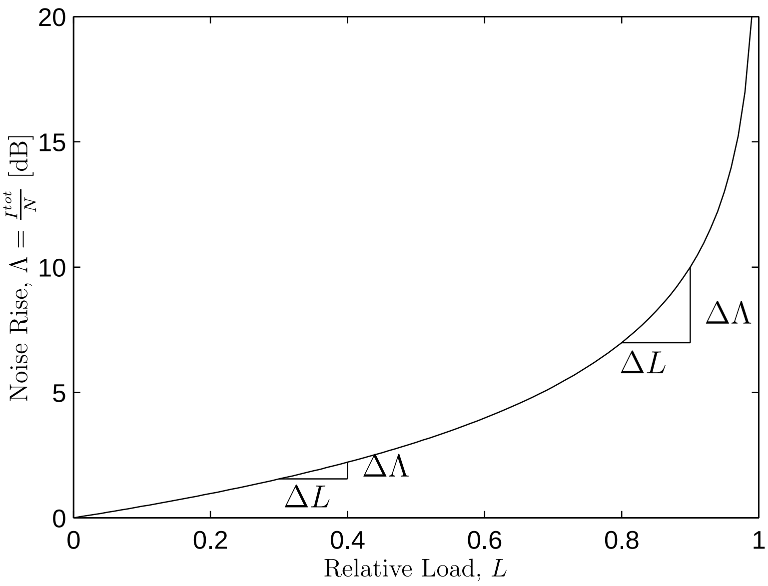


Figure 7.4: The nonlinear relation between relative load, L, and noise rise, $\Lambda = \frac{I^{tot}}{N}$ in logarithmic scale. ΔL could be the increase caused by admitting another user. This gives different noise rise contribution, $\Delta\Lambda$, depending on the system's initial load.

load is the uplink feasibility relative load, L^f, which is concerned with the entire system as a whole. A $L^f < 1$ corresponds to a stable system, in which there are transmission powers to support the allocated users.

The load according to both of these definitions depends on the situation in several base stations. Load estimates therefore benefit from incorporating information gathered in a wider area than what one base station covers. A number of centralized load estimates using power gain measurements have been proposed.

Using an estimate not based on measurements of I^{tot}, the resulting load can be predicted before a critical resource management decision is made. This is important for stability reasons. The estimates provides upper bounds on the true load. These upper bounds can be used to guarantee system stability.

Good utilization of available resource also requires accurate knowledge of the uplink load. A series of simulations indicates that the performance of the relative load estimates is insensitive to service mix, user location distribution and changes in radio environment [21, 39].

Just like the true load, estimated load can be described as oscillations on top of a trend in the time domain. Adaptive filtering has been applied to suppress these oscillations enabling even further increased utilization of available resources [40].

For further details, see the Licentiate Thesis [7] which was released during the year.

Accurate uplink load estimates constitute valuable input to radio resource management. However, efficient management also calls for flexible uplink services that can adapt to channel variations and network decisions. Distributed decisions to the mobiles enable fast link adaption in the uplink. Uplink transmission timing (UTT) is therefore proposed as a scheme to allow some load control support, while transmitting mainly when the channel is favorable. It utilizes channel state feedback in the form of power control commands, which already are available in the system. Simulations illustrate the transmission timing behavior, and also indicate that UTT is a power and inter-cell interference efficient scheme to transport data compared to traditional dedicated channels with continuous transmissions and to schemes where transmission decisions are random. For further details, see [41].

Erik Geijer Lundin, Fredrik Gunnarsson and Fredrik Gustafsson are working in this project, which is an ISIS project in cooperation with Ericsson Research.

7.5 Control, Fault Detection and Estimation in Data Networks

The core problem is that the standardized flow control implementations used in data networks are not designed for the traffic situations of today, and that it is next to impossible to upgrade the software in all Internet routers. However, some networks are redesigned, and IP is used in new and closed environments, such as transport networks between base stations in cellular radio systems. Therefore, it is plausible to discuss alternative traffic control algorithms and protocols. Furthermore, not only the data flow of each user is controlled, but also the total flows through each router to prevent overload situations. The total system can hence be seen as a complicated distributed control system with complex inter-connections between the control algorithms.

The main flow control protocol on the Internet is TCP. A protocol is a set of rules that organizes a part of the traffic and TCP organizes the send rate and the sequence of data. Using an addition to the data packets TCP can keep track of the correct order of the packets and also notice if a packets are lost. This information gives an indication about the capacity of the network and TCP keeps an internal estimate of this capacity. The estimate is increased when a packet is delivered successfully and decreased if the packets is lost. The way of increasing and decreasing was standardized at the birth of the Internet and therefore TCP is not so well suited for todays traffic scenario. A discussion about perfomrance measurements of TCP was made in [67].

To increase performance various suggestions have been made and today Random Early Detection, RED, is widely used. It is a mechnaism that drops or marks packets at the routers in order to damp TCPs oscillations and therefore keep the packet queue lengths constant. RED gives a local control strategy not based on knowledge of the entire network. When investigating the structure of other protocols, more controllers can be found. In investigation of the exisitng control structures in the layered network structure has been done in [8, Ch. 2]. A small *ns-2* simulation scenario is depicted in Figure 7.5.

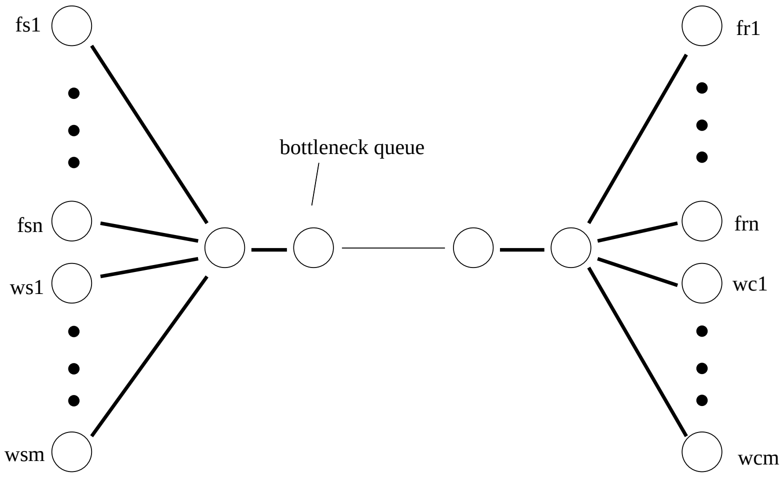


Figure 7.5: A *ns-2* simulation scenario with n file senders, fsi, with corresponding file receivers, fri, and m web servers, wsi, with corresponding web clients, wci.

Identification and Control in TCP networks

The original algorithm for control in communication network, were mainly based on heuristic arguments for design and parameter tuning. To be able to investigate the performance and improve control, there is a need for accurate models of the dynamics in the network. This work was focused on modeling of network queue dynamics in the routers, with the aim of improving the RED-like control. The dynamics were identified recursively as an AR model with a bias and the model output was used to based control decission on.

The results were presented at [19] and a little more thourough in [8, Ch. 3].

Nonuniform sampling

In a packet based network, all calculations are made on packet arrivals. The arrival times define the samping instants and an event based system is achieved. This kind of sampling is a special case of so called nonuniform sampling, which can occur in various applications. Many things differ when nonuniform instead of uniform sampling is used. For identification of models based on nonuniformly sampled signals, the frequency domain is suitable and therefore accurate calcualtion of the frequency response is crucial. The true frequency response, $Y(f)$,

$$Y(f) = \int_{-\infty}^{\infty} y(\tau)e^{-i2\pi f\tau}d\tau, \tag{7.2}$$

can be approximated using different interpolation techniques between the sampling instants. Given the nonuniform sampling times, t_k, the signal values are $y_k = y(t_k)$. In [8, Ch. 4], three main interpolations techniques were deployed and the accuracy of the resulting transform approximation, when a sinusoid was used as input, were investigated. The interpolation techniques were

polynomial spline interpolation of both the samples, y_k, and the integrand, $y_k e^{-i2\pi f t_k}$.

resampling with local polynomial models to be able to use uniform techniques to calculated the frequency response

basis expansion mainly with the sinc-functions to get similar results as in the uniform case,

$$\hat{y}(t) = \sum c_j \operatorname{sinc}(a_j(t - b_j)).$$

The basis functions can be placed both on an equidistant grida, $b_j = jT$, and nonequidistant grid, $b_j = t_j$.

Wireless simulations

The behavior of TCP is also related to characteristics of the links carrying IP packets. Wireless links typically divide IP packets into smaller datagrams, and may provide datagram reordering and retransmission to realize a reliable link. In UMTS, the packets are divided into smaller datagrams by the medium access control (MAC) layer, and retransmissions are handled by the radio link control (RLC) layer. Wireless resources are managed by Radio Network Controllers (RNC) through admission and congestion control to adapt the number of active users in the network, and channel switching to adapt the data rate of individual users. Figure 7.6 briefly depict the relevant UMTS architecture. To enable investigations on the TCP behavior from these components, models of RLC and RNC behavior are added to *ns-2*.

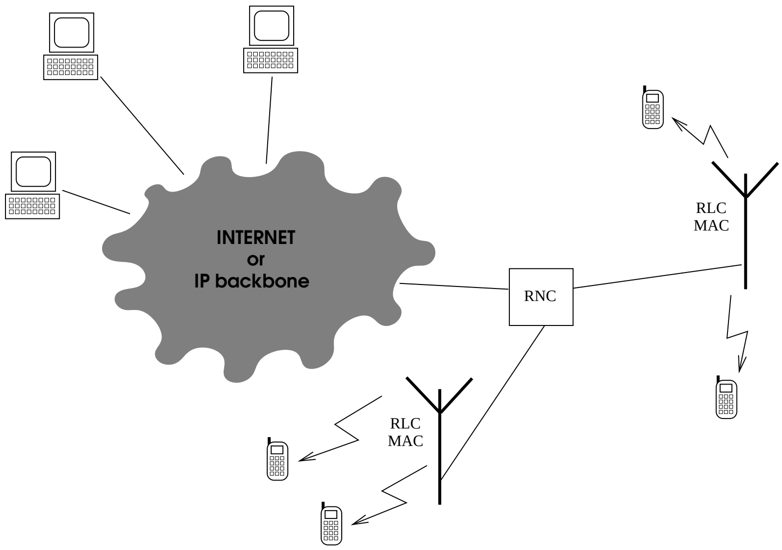


Figure 7.6: The UMTS terrestrial radio access network is connected to a wired network, an consists of mobiles, base stations and radio network controllers (RNC). The module described in this paper models RLC/MAC over the wireless links and typical RNC resource management algorithm behavior.

This was presented at the workshop [29], and further details are summarized in the report [102].

Frida Gunnarsson, Fredrik Gunnarsson and Fredrik Gustafsson are working in this project.

Chapter 8

Robotic Applications

8.1 Introduction

This work is to a large extent carried out in cooperation with ABB Robotics within the competence center ISIS (Information Systems for Industrial Control and Supervision). The overall aim of the work is to study and develop methods for improvement of the performance of robot control systems.

8.2 Iterative Learning Control

Iterative learning control (ILC) is a control method that utilizes a repetitive behavior that exists in many practical control applications, for example in the control of industrial manipulators. By using the error from previous "iterations" of the same action the error can be reduced. The structure of the problem is shown in Figure 8.1 where the output of the ILC algorithm is $u_{k+1}(t)$ defined for $0 \le t \le t_f$. Mathematically the algorithm can be

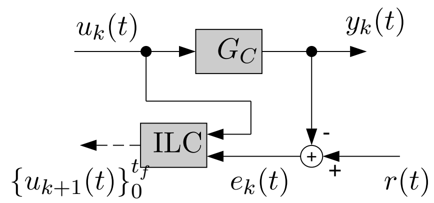


Figure 8.1: An example of a system controlled using ILC.

formulated as

$$u_{k+1} = Q(u_k + Le_k)$$

where u_k is the input to the controlled system and e_k is a measure of the control error. Q and L are operators that can be chosen by the user.

One of the main advantages of ILC compared to traditional feedback control solutions is that the operators Q and L do not have to be causal. The implications on stability and performance for ILC algorithms with causal Q and L operators are covered in [94]. The Current Iteration Tracking Error (CITE) ILC is discussed in [94] and in this approach an updating equation according to

$$u_{k+1} = Q(u_k + Le_{k+1})$$

is used. CITE therefore gives a feedback loop in combination with an iterative update of the ILC input. Clearly the advantage of non-causal operators in the ILC update equation does not exist here since the L operator acts as a feedback controller. The conclusion from [94] is that when using causal or CITE ILC the error will not in general converge to zero monotonically. This property is lost when the filters are no longer allowed to be non-causal.

Motivated by experimental results reported in the PhD thesis of Norrlöf (in 2000) a student project on "Iterative Learning Control of a Flexible Robot Arm Using Accelerometers" was launched in 2003. When controlling a standard industrial robot only measurements from the motors are available although it is the arm that should be controlled. ILC on the motor does not always give good result on the tool path tracking, and therefore additional sensors is a natural extension to increase the performance. In [28] the results from the project are reported. The process in the experiments is not a 6 degree-of-freedom (DOF) industrial manipulator but instead a one DOF flexible joint process from Quanser with an LQG controller. A two-mass model describes the physical process well and by neglecting the damping between the two masses a simplified equation for the arm torque balance is found

$$J_a\ddot{\theta}_a(t) + f_a\dot{\theta}_a(t) - k(\theta_m(t) - \theta_a(t)) = 0.$$

By also neglecting the friction an estimate of the arm angular position can be expressed as

$$\hat{\theta}_a(t) = \theta_m(t) - \frac{\hat{J}_a}{\hat{k}}\ddot{\theta}_a(t).$$

The variables $\theta_m(t)$ and $\ddot{\theta}_a(t)$ denote measured motor angle and measured acceleration, respectively. $\hat{J}_a$ and $\hat{k}$ are estimates of the arm inertia and the spring coefficient. With the error defined as $e_k = r - \hat{\theta}_a$ and an optimization based ILC scheme the algorithm converges after five iterations and the max error is reduced to approximately 4% of the error obtained without ILC. The ∞-norm of the error as a function of iteration is shown in Figure 8.2.

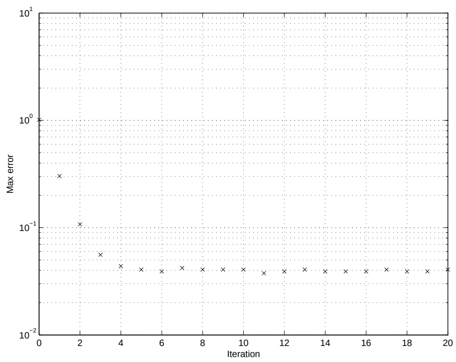


Figure 8.2: $\max_t \mid e_k(t) \mid$ as function of iteration number k.

8.3 Robot Identification

In control of industrial robots it is important to have good mathematical models describing the properties of the robot. This problem has been considered in [14] and [112] from different viewpoints. [14] presents results from identification of the physically parameterized three-mass model shown in Figure 8.3. It is shown that direct identification of the physical parameters using real data works well, but that the properties of the input signal have big influence on the estimated parameters.

In [112] a frequency domain method for multivariable identification is studied. The aim is to analyze how averaging over several periods of the input signal can be used in order to improve the model quality. In general this is a useful operation but in the case of periodic ripple disturbances present in robot control system some extra care has to be taken in order to achieve the desired improvement.

In some cases it can be advantageous to skip the modeling stage and aim

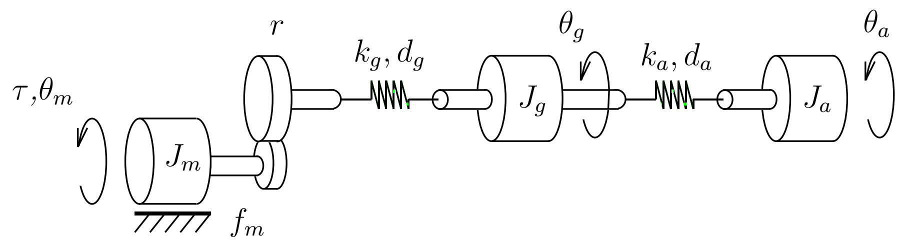


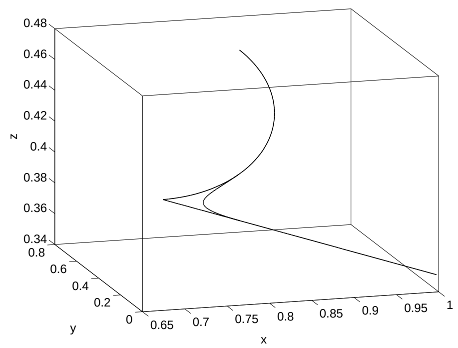
Figure 8.3: Three-mass flexible model.

for a direct tuning of the controller parameters. An example is given in [18] where a decoupling controller for a rigid two-link manipulator is studied.

8.4 Trajectory generation

The main problem of interest within trajectory generation for industrial robots is the “time-optimal planning problem”. A first step within the area is taken in the technical report [68]. The trajectory generation problem can be divided in two sub-problems. The fist problem is to generate a path with a given geometrical accuracy and the second problem relates to creating a velocity profile of the path. So far mainly the first sub-problem has been considered.

The path generation consists of creating a path in space and, as a second step, transform this path into joint space. As a result of a Master Thesis [158, 80] a first version of a Matlab Toolbox [107] for path generation has been developed. Using functions in the toolbox it is possible to create smooth paths in Cartesian space consisting of lines and arc-segments. In [68] and in [27] it is discussed how to make the smooth interconnection between the segments An example using the Matlab functions in [107] is shown in Figure 8.4 where two segments, a line and an arc, are connected and the resulting path is shown in 3 dimensions. The commands to generate the path aew shown to the right.




```
esec = emptysec([1 0.02 0.35])
lsec = moveline(esec,[0.7 0.2 0.4],0.1)
csec = movecirc(lsec,[0.85 0.35 0.45],...
        [0.74 0.49 0.5],0.1,1)
rpath = makepath(lsec,csec)
plotpath(rpath,2)
```

Figure 8.4: Example from the Matlab Path Generation Toolbox (PGT). The smooth path is shown together with the line and arc segments.

Chapter 9

Optimization for Control and Signal Processing

9.1 Introduction

The research in optimization for control and signal processing is currently focused on efficient optimization algorithms for robustness and stability analysis of control systems. Work has also been carried out to apply iterative feedback tuning to auto-tuning of PID controllers.

9.2 Optimization Algorithms for Robustness Analysis

In this project we study how to construct efficient Interior-Point (IP) algorithms for the Semidefinite Programs (SDPs) that originate from the Kalman-Yakubovich-Popov (KYP) lemma. They have several applications, e.g., linear system design and analysis, robust control analysis using integral quadratic constraints, quadratic Lyapunov function search, and filter design.

Typically standard SDP solvers cannot handle KYP-SDPs of more than small to medium size in reasonable time, typically the limit is about 50 state-variables, resulting in roughly 1000 optimization variables. With specially tailored KYP-SDP-solvers problems with several hundred state-variables, corresponding to roughly tenths of thousands of variables can be handled.

The computational complexity stems from the cost of assembling and solving the equations for the search directions in the IP algorithms. Two avenues have been investigated to circumvent this problem. One is to use iterative methods for solving the equations. The results have been reported in [35, 83]. In that work is also presented a proof of polynomial complexity for general potential-reductions IP algorithms when using inexact search directions resulting from iterative methods.

Another way of attacking the above problem is to consider the dual problem and make use of an image representation of some of the constraints. This will reduce the number of variables in the dual problem such that the computation complexity is reduced with two orders of magnitude with respect to the state-dimension. This work has bee presented in [77]. It has been compared with the method using inexact search directions in [78, 23]. A Matlab implementation of the code is publically available at http://www.control.isy.liu.se/research/authors/reports/2517/kypd.html and is described in[90]. The solver is one of the solvers in YALMIP.

It is possible to reduce the computational complexity even further by diagonalizing the system matrix. This has been described in [55].

Applications related to the above mentioned methods for stability analysis of nonlinear systems and for clearance of flight control laws have been reported in [84, 116]

9.3 Relay Auto-Tuning of PID Controllers

In this project ideas from iterative feedback tuning (IFT) are incorporated into relay auto-tuning to give specified phase margin and bandwidth. Good tuning performance according to the specified bandwidth and phase margin can be obtained and the limitation of the standard relay auto-tuning technique using a version of Ziegler-Nichols formula can be eliminated. Furthermore, by using common modeling assumptions for the relay system, some of the required derivatives in the IFT algorithm can be derived analytically. The algorithm has been tested on a laboratory coupled tank, and good tuning results has been demonstrated. The results have been published in [12].

Appendix A

Personnel

Lennart Ljung is professor and head of the control group since 1976. He was born in 1946 and received his Ph.D. in Automatic Control from Lund Institute of Technology in 1974. He is a member of the Royal Swedish Academy of Engineering Sciences (IVA) and the Royal Swedish Academy of Sciences (KVA), and an IFAC Advisor. He is also an IEEE Fellow and associate editor of several journals. He has received honorary doctor's degrees from the Baltic State Technical University in S:t Petersburg Russia (1996), and from Uppsala University, Uppsala, Sweden (1998).
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Svante Gunnarsson was born in 1959. He received his M.Sc. in 1983, his Licentiate's degree in 1986 and his Ph.D. in 1988 all from Linköping University. From 1989 he was associate professor at the department, and from 2002 professor. His research interests are system identification and adaptive control.
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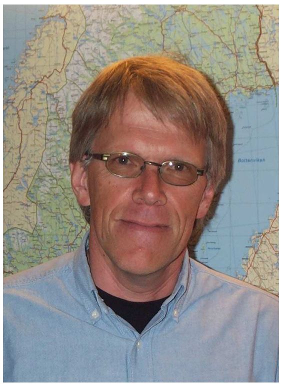

Fredrik Gustafsson was born in 1964. He received the M.S. degree in electrical engineering in 1988 and the Ph.D. degree in automatic control in 1992, both from Linköping University, Sweden. He is currently professor in Communication Systems at the Department of Electrical Engineering at Linköping University. His research is focused on statistical methods in system identification, signal processing and adaptive filtering, with applications to communication, avionic and automotive systems.
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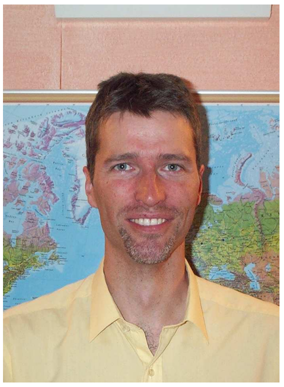

Inger Klein is a associate professor at the department. She was born in 1964. She received her M.Sc. in 1987, her Licentiate's degree in 1990, and her Ph.D. in 1993, all from Linköping University. Her research interest is diagnosis, fault detection and fault isolation, in particular for Discrete Event Systems.
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Anders Hansson was born in Trelleborg, Sweden, in 1964. He received the M.Sc. 1989, Lic.Eng. in 1991, and the Ph.D. in 1995, all from Lund University, Lund, Sweden. From 1995 to 1998 he was employed by the Information Systems Lab, Stanford University. From 1998 to 2000 he was associate professor at Automatic Control, KTH, Stockholm. From 2001 he is an associate professor at the Division of Automatic Control, Linköping University. His research interests are within the fields of optimal control, stochastic control, linear systems, signal processing, fuzzy logic, applications of control, image processing, and telecommunications.
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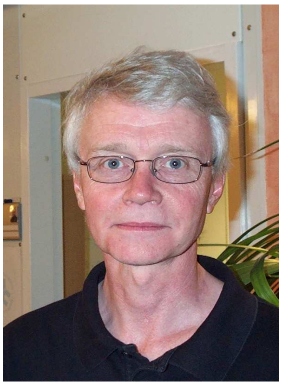

Kent Hartman was born in 1951. He received his M. Sc. in 1977 Applied Physics and Electrical Engineering at Linköping University, Department of Biomedical Engineering. He is an associate lecturer in the Control Group.
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Mikael Norrlöf was born in 1971. He received his M.Sc in Computer Science and Engineering 1996, his Lic.Eng. in 1998 and his Ph.D. in 2000, all at Linköping University. His current research interests include Iterative Learning Control as well as modeling, nonlinear control, trajectory generation, and identification of industrial robots.
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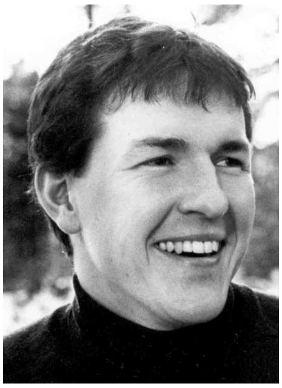

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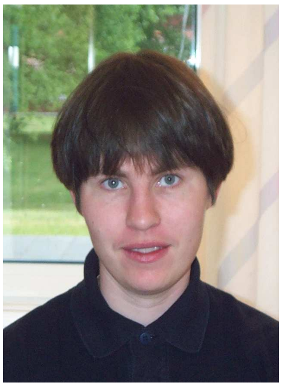

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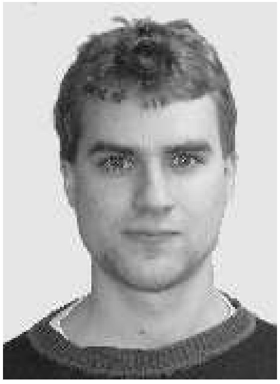

Jacob Roll was born in 1974. He received his M.Sc. in Applied Physics and Electrical Engineering in 1999 and his Lic.Eng. in 2001 and his PhD in 2003 all at Linköping University. His research interests are in system identification and hybrid systems.
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Rickard Karlsson was born in 1970. He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 and his Lic.Eng. in 2002 both at Linköping University. He is also employed by Saab Bofors Dynamics from where he is on leave to complete his Ph.D.
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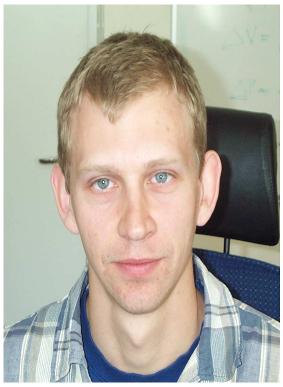

Frida Gunnarsson was born in 1977. She received her M.Sc. in Applied Physics and Electrical Engineering in 2000 and Her Lic.Eng. in 2003 both at Linköping University.
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David Lindgren was born in 1968. He received his M.Sc. in Computer Science and Engineering in 2000 and his Lic.Eng. in 2002, both from Linköping University. His research interests are in subspace selection techniques, mainly for sensor applications.
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Christina Grönwall was born in 1968. She received her M.Sc. in Applied Physics and Electrical Engineering in 1992, from Luleå University of Technology and her Lic.Eng. in 2001 from Linköping University. She is employed by FOI, Linköping.
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Ragnar Wallin was born in 1962. He received his M.Sc. in Electrical Engineering in 1998 and his Lic.Eng. in 2000 both from the Royal Institute of Technology, Stockholm. His research interests are in optimization algorithms, mainly for gain scheduling applications.
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Magnus Åkerblad was born in 1976. He received his M.Sc. in Materials Technology in 2000 and his Lic.Eng in 2002 both at the Royal Institute of Technology, Stockholm. His research interests include optimization for MPC.
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Thomas Schön was born in 1977. In 2001 he received his BSc degree in Business Administration and Economics, and his MSc degree in Applied Physics and Electrical Engineering and his Lic.Eng. in 2003 all at Linköping University. His research interests are in signal processing and system identification.
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Joakim Svensèn, was born in 1977. He is employed as research engineer at the Division since December 2000, where he is responsible for the laboratory equipment.
`email: joasv@isy.liu.se`

Sören Hansson is employed as research engineer at the Division on a part time basis, where he is responsible for the laboratory equipment.
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Per Stolpe is employed as research engineer at the Division on a part time basis.
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Ulla Salaneck is secretary for the control group.
`email: ulla@isy.liu.se`

Visitors

- Alexander Nazin, Institute of Control Sciences, Moscow. January 14 - February 7 and November 10 - December 20, 2003.
- Per-Olof Gutman, Technion, Haifa, September 10-12, 2003.
- Rimantas Pupeikis, Vilnius, Lithuania. November 2002 - June 2003.
- Marc Bodson, University of Utah, USA, May 20 -23, 2003.
- Simone Paoletti, Universita' di Siena, Italy, November 2002 - April 2003.
- Manfred Morari, ETH, Zürich, Switzerland, April 24-25, 2003.
- Alexander Fradkov, St. Petersburg, Russia, March 31 - April 18, 2003.
- Bjarne Foss, NTNU - Norwegian University of Science and Technology, April 10-11, 2003.
- Sarunas Paulikas, Vilnius, Lithuania, February - March. 2003.
- Dalius Navakauskas, Vilnius, Lithuania, October 2002 - March 2003 and November 2003 - February 2004
- Chung-Yao Kao, Mittag-Leffler Institute, March 6 - 7, 2003.

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. 200 participants. Lecturer: Torkel Glad.

  Y Applied Physics and Electrical Engineering. 150 participants. Lecturer: Lennart Ljung.

  D Computer Engineering Program. 90 participants. Lecturer: Fredrik Tjärnström.

  I Industrial Engineering and Management. 155 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. 67 participants. Lecturer: Anders Hansson.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management and Mechanical Engineering Programs. Multivariable systems, Sampled data systems, LQG-control. 20 Participants. Lecturer: Mikael Norrlöf.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Modelling, Bond graphs, System Identification, 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. 60 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. 80 participants. Lecturer: Torkel Glad.

- *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. 90 participants. Lecturer: Inger Klein.

- *Real Time Process Control* (Realtidsprocesser och reglering). For the Information Technology Program. Real time systems. PID control. 30 participants. Lecturer: Inger Klein.

- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, controllability, observability, feedback control. 21 participants. Lecturer: Inger Klein.

- *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, 45 Participants. Lecturer: Anders Hansson.

- *Automatic Control Project Course* (Reglerteknik - projektkurs M) For the Mechanical Engineering Program. Project work, mainly carried out in industri. The projects involve modeling, controller design and implementation. 8 Participants. Lecturer: Svante Gunnarsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Available for several Engineering Programs. 900 Participants. Lecturer: Fredrik Gustafsson.

- *Project work* (Ingenjörsprojekt Y). Develop an understanding of what engineering is all about and how the work is performed. - Administration, planning, communication, documentation and presentation of project work, 20 Participants. Lecturer: Anders Hansson and Kent Hartman.

- *Perspectives to computer technology* (Perspektiv på datateknik). Project work with focus on computer technology, 12 Participants. Lecturer: Kent Hartman.

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

- *Automatic control, EI* (Electrical Engineering) 5 units, 21 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, 28 participants. Contents: Sequential control and logic controllers. A typical industrial control system. Lecturer: Kent Hartman.

- *Automatic control, MI/KI* (Mechanical Engineering and Chemical Engineering) 4 units, 70 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

- *Adaptive Filtering and Change Detection.* Lecturer Fredrik Gustafsson, Literature: Fredrik Gustafsson, Adaptive filtering and change detection, John Wiley & Sons.
- *Robust Multivariable Control.* Lecturer Anders Helmersson, Literature: Zhou, J. C. Doyle and K. Glover: Robust and Optimal Control, Prentice Hall 1995.
- *Nonlinear systems.* Lecturer Torkel Glad. Literature: Lecture Notes.
- *Robot modeling and control.* Lecturer Mikael Norrlöf. Literature: e.g. M.W. Spong and M. Vidyasagar: Robot Dynamics and Control.

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 11 Intel-based laptop computers. In the laboratory, mainly used by students in the different courses, there are a lot of different processes and 27 Intel-based computers for measurement and control. The students also got 24-hours access to 64 Sun Ultra 10 workstation in an Ethernet based computer network.

Comments and questions on the equipment can be directed to Joakim Svensén.

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

- An Ethernet based 100baseT TCP/IP network
- 24 Sunblade 100
- 8 Sun Ultra 10
- 2 Dell OptiPlex PC:s
- 1 HP LaserJet 8100DN Postscript laser printer
- 1 HP LaserJet 5 MPPostscript laser printer
- 1 Xerox Phaser 8200 solid ink-jet color printer

The Sun workstations run Solaris 2.8 and CDE (Common Desktop Environment). The software used in this network is mainly for advanced calculations and documenting. Among the mathematical programs are Matlab, Maple, Mathematica, 20sim, MathModelica, 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:

- 7 Dell Latitude (Pentium,Pentium II and Pentium III of various speed)
- 1 Acer TravelMate 516TE

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 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
- 1 Mobile robot Pioneer DX2 with laser navigation
- 1 Rotary flexible joint process
- 6 Dell Workstation 400
- 8 Network Crimson single Pentium III with dSPACE signal processing cards
- 8 Dell Precision 340 with National Instruments data acquisition cards
- 3 Dell Workstation 340
- 2 Dell Workstation 220 with Allan Bradley SLC500 PLC system
- 1 OKI 6100 laser printer

Appendix D

Seminars

- *Identification of piecewise affine models using bounded-noise assumption.* **Simone Paoletti,** University of Siena, Siena, Italy, January 16, 2003.

- *On Nonparametric Approach to Frontier Estimatior.* **Alexander Nazin,** Russian Academy of Science, Moscow, Russia, January 23, 2003.

- *Error-Driven QoS Management in Real-Time Databases.* **Mehdi Amirijoo**, Linköpings universitet, January 30, 2003.

- *Restoration of Lost Segments of Voiced Speech.* **Sarunas Paulikas,** Vilnius Gediminas Technical University, Vilnius, February 13, 2003.

- *Identification of cellular networks and critical genes from global expression measurements - bridging from technology to the clinic.* **Jesper Tegner,** Linköpings universitet, February 20, 2003.

- *Control of the Aero-Electric Power Station - an exciting QFT.* **Per-Olof Gutman,** Israel Institute of Technology, February 26, 2003.

- *Controlled Lagrangian Systems.* **Johan Hamberg,** FOI, Linköping, february 27, 2003.

- *Efficient Computational Algorithms for IQC Analysis.* **Chung-Yao Kao,** Mittag-Leffler Institute, March 6, 2003.

- *Rank reduction - data-mining from a linear algebra perspective.* **Lars Eldén**, Department of Mathematics, Linköpings universitet, March 20, 2003.

- *Data Mining: Opportunities and Challenges.* **Stefan Arnborg,** Royal Institute of Technology, Stockholm, April 3, 2003.

- *Cypbernetical Physics: Studying Physical System by Means of Control.* **Alexander Fradkov,** Russian Academy of Science, April 8, 2003.

- *Control of positive systems - theory and applications.* **Bjarne Foss,** Norwegian University of Science and Technology, April 10, 2003.

- *Control of Hybrid Systems.* **Manfred Morari,** ETH, Zurich, April 24, 2003.

- *Multi-user detection for non-Gaussian noise.* **Abdelhak Zoubir,** Darmstadt University of Technology. May 6, 2003.

- *Systems Biology - Some Basic Ideas.* **Mats Jirstrand,** InNetics, May 16, 2003.

- *Cancellation of Periodic Disturbances with Unknown Frequency.* **Marc Bodson,** University of Utah, May 20, 2003.

- *Reconfigurable Flight Control.* **Marc Bodson,** University of Utah, May 22, 2003.

- *Interior Methods for Optimization.* **Anders Forsgren,** Optimization and Systems Theory, Royal Institute of Technology, Stockholm, May 22, 2003.

- *An Overview of the MSTAR Automatic Target Recognition Research Program.* **Bill Pierson,** FOI, Linköping, June 5, 2003.

- *Reduced gradients, automatic differentiation and adjoint variables.* **Per Olov Lindberg,** Department of Mathematcis, Linköpings universitet, September 18, 2003.

- *Real-time bleaching control at pulp mills.* **Mikael Rönnqvist**, Department of Mathematcis, Linköpings universitet, September 18, 2003.

- *Relaxed Dynamic Programming.* **Bo Lincoln**, Lund University, September 25, 2003.

- *Filtering and maximum likelihood estimation in non-linear non-gaussian state space models.* **Tobias Rydén**, Lund University, October 23, 2003.

- *Multiple antenna elements in wireless communication.* **Mattias Wennström,** Atelier, November 6, 2003.

- *Intelligent Autonomous Systems.* **Dr. David Nicholson,** BAE Systems, November 20, 2003.

Appendix E

Travel and Conferences

Martin Enqvist participated in the 13th IFAC Symposium on System Identification in Rotterdam, The Netherlands, August 27-29 and in the ERNSI Workshop on System Identification in Noordwijkerhout, The Netherlands, October 6-8.

Erik Geijer Lundin participated at Wireless Communications and Networking Conference, New Orleans, March 2003, 9th Annual Swedish Workshop on Wireless Systems 2003, Täby, December 2003.

Markus Gerdin participated at the 13th IFAC Symposium on System Identification, Rotterdam, August 2003, ERNSI Workshop System Identification, Noordwijkerhout, October 2003, 42nd IEEE Conference on Decision and Control, Maui, December 2003.

Jonas Gillberg participated at the World Congress on Automatic Control, Barcelona, July 2002, Workshop on Semidefinite Programming, Toulouse, September 2002

Torkel Glad was a visitor at the Mittag-Leffler Institute March 9 – April 6 2003 and took part in the Swedish-Chinese conference August 21 -22 2003.

Fredrik Gunnarsson visited Bejing University of Post and Telecommunications, Beijing, China, February, 2003 and participated at the Vehicular Technology Conference, Orlando, FL, USA, October, 2003, 9th Annual Swedish Workshop on Wireless Systems, Täby, Stockholm, December, 2003.

Frida Gunnarsson participated in the First Swedish National Computer Networking Workshop, Arlanda stad, Sweden, September, 2003 and the 42nd IEEE Conference on Decision and Control, Maui, USA, December, 2003.

Svante Gunnarsson Attended Mekatronikmötet 2003, Gothenburg, August, 2003, visited MIT, USA, May 2003, and Danmarks Tekniska Högskola, Lyngby, Denmark, October 2003.

Fredrik Gustafsson participated at the 13th IFAC Symposium on System Identification (SYSID-2003), Rotterdam, The Netherlands, August, 2003.

Anders Hansson attended the IMA Workshop on Semidefinite Programming and Robust Optimization, March. In June he gave a short course on Convex Optimization for Control and Signal Processing at Chalmers University of Technology, Göteborg. In June he attended the 4th IFAC Symposium on Robust Control Design, Milano, and visited University of Sienna, Sienna. In November he visited Aalborg University where he was member of an examination committee for a PhD degree. In December he attended IEEE Conference on Decision and Control, Maui, USA. He also visited UCLA, Los Angeles, USA.

Kent Hartman participated at the Tekit-dagen, Linköping, April 2003, Lithgymdagen, Linköping, May 2003, Kungl. Ingenjörsvetenskapsakademien "Morgondagens Ingenjör", Linköping, Novembers, 2003, ISIS workshop, Linköping, Novembers 2003, CUL-dagen, Linköping, Novembers, 2003.

Ola Härkegård participated at the European Control Conference, Cambridge, UK, September, 2003.

Rickard Karlsson participated in IEEE Statistical Signal Processing Workshop, St Louis, USA, October, 2003.

Inger Klein visited Vilnius Gediminas Technical University, Lithuania, 15-16 May 2003. She participated in the Fourteenth International Workshop on Principles of Diagnosis (DX-03), Washington, D.C., June 2003 and attended the 5th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes (SAFEPROCESS 2003), June 2003. She participated in the 42nd IEEE Conference on Decision and Control (CDC 2003), Maui, Hawaii, December 2003.

Lennart Ljung participated in the IEEE Applications for Industry Workshop, Vancouver, Canada, April 26 - 30, took part in a workshop at University of Edmonton, Canada on May 1, visited the Laboratoired'Atomatique at EPFL, Lausanne on May 9, visited Vilnius Gediminas Technical University, Vilnius, Lithuania, May 15-16 and Zürich, May 19. He participated in the 1st Swedish-Chinese Conference on Control, Stockholm, on August 21- 22, the 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, August 26 - 30, the The European Conference on Control, ECC'03, Cambridge, England, August 30 - September 4. He visited Paulstra CRC, Grand Rapids, MI, September 23 - 25. He took part in the ERNSI Workshop, Noordwijkerhout, The Netherlands, October 6-8, and the Matlab Conference in Copenhagen on October 21-22. He visited Vrije Univerisity, Brussels on November 27-28, and finally participated in the 42nd IEEE Conference on Decision and Control, Maui, Hawaii, December 8-13.

Mikael Norrlöf participated at the Mechatronics conference Mekatronikmöte 2003, Göteborg, August 2003, and at the Iterative Learning Control International Summer School, Utah State University, Logan, Utah, USA, June 8-13 2003.

Jacob Roll participated at the 13th IFAC Symposium on System Identification, Rotterdam, The Netherlands, August, 2003, European Control Conference, Cambridge, UK, September 3, 2003, ERNSI Workshop, Noordwijkerhout, The Netherlands, October 6-8, 2003.

Ulla Salaneck visited Vilnius Gediminas Technical University, Lithuania, 15-16 May 2003, took part in the First Swedish-Chinese Control Conference in Stockholm, August 21-22 and the ERNSI Workshop, Noordwijkerhout, The Netherlands, October 6-8, 2003.

Thomas Schön participated at the 13th IFAC Symposium on System Identification (SYSID-2003), Rotterdam, The Netherlands, August, 2003, ERNSI Workshop System Identification 2003, Noordwijkerhout, The Netherlands, October 2003, 42nd IEEE Conference on Decision and Control, Maui, Hawaii, USA, December, 2003.

Ragnar Wallin participated at the 4th IFAC symposium on robust control design, Milan, Italy, June, 2003 and the Mini-Workshop on Convex Optimization Techniques for Control Systems Analysis and Design, Universita' di Siena, Italy, June, 2003.

Erik Wernholt participated in the ERNSI Workshop on System Identification in Noordwijkerhout, The Netherlands, October 6-8.

Appendix F

Lectures by the Staff

- Martin Enqvist: *Linear Models of Nonlinear FIR Systems with Gaussian Inputs*, 13th IFAC Symposium on System Identification, Rotterdam, The Netherlands, August 29, 2003.
- Martin Enqvist: *Input signals for LTI approximations of nonlinear systems*, ERNSI Workshop on System Identification, Noordwijkerhout, The Netherlands, October 6, 2003.
- Erik Geijer Lundin *Uplink Load in WCDMA with Different Availability of Measurements*, Proceedings of VTC, Spring, 2003.
- Erik Geijer Lundin *Adaptive Filtering Applied to an Uplink Load Estimate in WCDMA*, Proceedings of VTC, Spring, 2003.
- Erik Geijer Lundin *Uplink Load Estimation in WCDMA*, Proceedings of WCNC, 2003.
- Erik Geijer Lundin *Particle filter and Cramer-Rao lower bound for underwater navigation*, Proceedings of ICASSP, 2003.
- Markus Gerdin: *Parameter estimation in linear differential-algebraic equations*, 13th IFAC Symposium on System Identification, Rotterdam, The Netherlands, August 29, 2003.
- Markus Gerdin: *Parameter estimation in differential-algebraic equations*, ERNSI Workshop System Identification, Noordwijkerhout, The Netherlands, October 6, 2003.

- Torkel Glad: *Lyapunov functions for control of rigid bodies with applications to aircraft control.* Institut Mittag-Leffler. March 20, 2003.
- Torkel Glad: *How will object oriented modelling affect control theory?* Swedish-Chinese conference. August 22 2003.
- Fredrik Gunnarsson: *Power control and wireless communications networks stability*, Beijing University of Post and Telecommunications, Beijing, China, February 25, 2003.)
- Fredrik Gunnarsson: *Uplink transmission timing in WCDMA*, IEEE Vehicular Technology Conference, Orlando, FL, USA, October 9, 2003.)
- Fredrik Gunnarsson: *IC, PC, PIC och WCDMA*, 9th Annual Swedish Workshop on Wireless Systems, Täby, Stockholm, December 9, 2003.)
- Frida Gunnarsson: *On Modeling and Control of Network Queue Dynamics*, Ericsson Research, Linkoping Sweden, November 21, 2003.
- Frida Gunnarsson: *Controlling Internet Queue Dynamics using Recursively Identified Models*, 42nd IEEE Conference on Decision and Control, Maui, USA, December 9, 2003.
- Svante Gunnarsson: *Iterative learning control of a flexible robot arm using accelerometers*, Mekatronikmötet 2003, Gothenburg, August, 2003.
- Fredrik Gustafsson: *Particle filters for prediction of chaos*, 13th IFAC Symposium on System Identification (SYSID-2003), Rotterdam, The Netherlands, August 28, 2003.
- Fredrik Gustafsson: *Sensor Fusion*, invited talk at the Sensor Network Workshop at the Department of Physics, Linköping University, 2003.
- Anders Hansson: *System Modeling in Linear Fractional Transformation Form*, SAAB, Linköping, February 12, 2003.
- Anders Hansson: *LFT Methods in Aeronautics*, FOI, Stockholm, December 2, 2003.
- Ola Härkegård: *Styrsignalsfördelning hos system med redundanta aktuatorer*, Dept. of Autonomous Systems, FOI, Stockholm, Sweden, May 7, 2003.

- Ola Härkegård: *Resolving actuator redundancy - Control allocation vs. linear quadratic control*, European Control Conference, Cambridge, UK, September 3, 2003.

- Ola Härkegård: *Nonlinear multivariable flight control*, Dept. of Automatic Control, Lund University, Sweden, November 13, 2003.

- Rickard Karlsson: *Particle Filter for Underwater Terrain Navigation*, IEEE Statistical Signal Processing Workshop, St Louis, USA, October, 2003.

- Lennart Ljung: *From Data to Model: A status report on system identification: Advanced Process Control,* IEEE Applications for Industry Workshop, Vancouver, Canada. April 29, 2003.

- Lennart Ljung *The Art and Science of System Identification*, Full Day Workshop, University of Edmonton, Canada, May 1, 2003.

- Lennart Ljung *From Data to Model: A status report on system identification*, Laboratoired'Atomatique at EPFL, Lausanne, May 9, 2003.

- Lennart Ljung *An overview of Linkoping University and Control Research there*, Vilnius Gediminas Technical University, Vilnius, Lithuania, May 16, 2003.

- Lennart Ljung *Non-linear Black-box models - A Model on Demand Perspective*, 1st Swedish-Chinese Conference on Control, Stockholm, August 22, 2003.

- Lennart Ljung *Structure Selection with ANOVA - Local Linear Models*, The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 27, 2003.

- Lennart Ljung *VERSION 6 of the System identification toolbox*, The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 28, 2003.

- Lennart Ljung *Initialization of Physical parameter estimates*, The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 29, 2003.

- Lennart Ljung *Educational Aspects of identification software user interfaces*, The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 29, 2003.

- Lennart Ljung *Aspects and experiences of user choices in subspace identification method*, The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 29, 2003.

- Lennart Ljung *Suboptimal bootstrap method for structure detection in nonlinear output-error models*, (Author; S.L. Kukreja), The 13th IFAC Symposium on System identification, SYSID'03, Rotterdam, The Netherlands, August 29, 2003.

- Lennart Ljung *Initialization aspects for subspace and output-error identification methods*, The European Conference on Control, ECC'03, Cambridge, England, September 2, 2003.

- Lennart Ljung *From Data to Model: A status report on system identification*, Plenary presentation at Paulstra's 2nd International Conference, Paulstra CRC, Grand Rapids, Michigan, October 1, 2003.

- Lennart Ljung *Version 6 of the System Identification Toolbox – Frequency Domain data and Process Models* Oct 21:, The MATLAB Nordic Conference, Copenhagen, October 21, 2003.

- Lennart Ljung *The ISIS Competence Center*, Presentation at the Workshop: Cross Disciplinary research and the role of Industry, 42nd IEEE Conference on Decision and Control, Maui, Hawaii, December 8, 2003.

- Lennart Ljung *Challenges of Nonlinear System Identification. The Bode Lecture*, 42nd IEEE Conference on Decision and Control, Maui, Hawaii, December 12, 2003.

- Mikael Norrlöf: *Path generation for industrial robots*, Mekatronikmöte 2003, Göteborg, Sweden, May 28, 2003.

- Mikael Norrlöf: *From ILC Analysis and Design to Experiments and Eventually a Product*, Tutorial lecture at the Iterative Learning Control International Summer School, Utah State University, Logan, Utah, USA, June 9, 2003.

- Mikael Norrlöf: *Trajectory generation for industrial robots*, ABB Robotics, Västerås, Sweden, November 28, 2003.

- Jacob Roll: *Local and Piecewise Affine Approaches to System Identification*, KTH, Stockholm, May 22, 2003.

- Jacob Roll: *Local Modelling Using Direct Weight Optimization*, Lund University, Lund, June 5, 2003.

- Jacob Roll: *Local Modelling of Nonlinear Dynamic Systems Using Direct Weight Optimization*, 13th IFAC Symposium on System Identification, Rotterdam, The Netherlands, August 29, 2003.

- Jacob Roll: *Local Modelling with A Priori Known Bounds Using Direct Weight Optimization*, European Control Conference, Cambridge, UK, September 3, 2003.

- Thomas Schön: *Particle filters for system identification of state-space models linear in either parameters or states*, 13th IFAC Symposium on System Identification (SYSID-2003), Rotterdam, The Netherlands, August 28, 2003.

- Thomas Schön: *Using particle filters for system identification*, ERNSI Workshop System Identification 2003, Noordwijkerhout, The Netherlands, October 7, 2003.

- Thomas Schön: *A modeling and filtering framework for linear differential-algebraic equations*, 42nd IEEE Conference on Decision and Control, Maui, Hawaii, USA, December 9, 2003.

- Ragnar Wallin: *Comparison of two structure-exploiting optimization algorithms for integral quadratic constraints*, 4th IFAC symposium on robust control design, Milan, Italy, June 25, 2003.

- Ragnar Wallin: *Efficiently solving semidefinite programs originating from the KYP lemma using standard primal-dual solvers*, Mini-Workshop on Convex Optimization Techniques for Control Systems Analysis and Design, Universita' di Siena, Italy, June 30, 2003.

Appendix G

Publications

PhD Theses

[1] Johan Löfberg. *Minimax Approaches to Robust Model Predictive Control*. PhD thesis No 812, Department of Electrical Engineering, Linköping University, SE–581 83 Linköping, Sweden, April 2003.

[2] Jacob Roll. *Local and Piecewise Affine Approaches to System Identification*. PhD thesis No 802, Department of Electrical Engineering, Linköping University, SE–581 83 Linköping, Sweden, April 2003.

[3] Jonas Elbornsson. *Analysis, Estimation and Compensation of Mismatch Effects in A/D Converters*. PhD thesis No 811 , Department of Electrical Engineering, Linköping University, SE–581 83 Linköping, Sweden, April 2003.

[4] Ola Härkegård. *Backstepping and Control Allocation with Applications to Flight Control*. PhD thesis No 820, Department of Electrical Engineering, Linköping University, SE–581 83 Linköping, Sweden, May 2003.

Licentiate Theses

[5] Thomas Schön. On computational methods for nonlinear estimation. Technical Report Licentiate Thesis no. 1047, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[6] Martin Enqvist. Some results on linear models of nonlinear systems. Technical Report Licentiate Thesis no. 1046, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[7] Erik Geijer Lundin. Uplink load in cdma cellular systems. Licentiate thesis LIU-TEK-LIC-2003:44 Licentiate Thesis no. 1045, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[8] Frida Gunnarsson. On modeling and control of network queue dynamics. Technical Report Licentiate Thesis no. 1048, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[9] Svante Björklund. A survey and comparison of time-delay estimation methods in linear systems. Technical Report Licentiate Thesis no. 1061, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

Journal Papers and Book Chapters

[10] Wolfgang Reinelt and Lennart Ljung. Robust control of identified models with mixed parametric and non-parametric uncertainties. *European Journal of Control*, 9:351–358, Oct 2003.

[11] Fredrik Tjärnström and Lennart Ljung. Variance properties of a two-step arx estimation procedure. *European Journal of Control*, 9:400 –408, Nov 2003.

[12] W. K. Ho, Y. Hong, A. Hansson, H. Hjalmarsson, and J. W. Deng. Relay auto-tuning of PID controllers using iterative feedback tuning. *Automatica*, 39(1):149–157, Jan 2003.

[13] W. K. Ho, Y. Hong, Anders Hansson, H. Hjalmarsson, and J. W. Deng. Relay auto-tuning of pid controllers using iterative feedback tuning. *Automatica*, 39(1), Jan 2003.

[14] M. Östring, Svante Gunnarsson, and Mikael Norrlöf. Closed loop identification of an industrial robot containing flexibilities. *Control Engineering Practice*, 11(3):291–300, Mar 2003.

[15] Fredrik Gunnarsson and Fredrik Gustafsson. Control theory aspects of power control in UMTS. *Control Engineering Practice*, 11(10):1113–1125, Oct 2003.

[16] Lennart Ljung. Linear system identification as curve fitting. New Directions in Mathematical Systems Theory and Optimization. *Springer Lecutre Notes in Control and Information*, Springer Verlag, Berlin, 286:203 – 215, Dec 2003.

[17] Fredrik Tjärnström. Variance analysis of l2 model reduction when undermodeling - the output error cases. *Automatica*, 39(10), Oct 2003.

[18] Svante Gunnarsson, V. Collignon, and O. Rousseaux. Tuning of a decoupling controller for a 2x2 system using iterative feedback tuning. *Control Engineering Practice*, 11:1035–1041, 2003.

Conference Papers

[19] Frida Gunnarsson, Fredrik Gunnarsson, and Fredrik Gustafsson. Controlling internet queue dynamics using recursively identified models. In *Proceedings of the 42nd IEEE Conference on Decision and Control*, Maui, HI, Dec 2003.

[20] Thomas Schön, Fredrik Gustafsson, and Anders Hansson. A note on state estimation as a convex optimization problem. In *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 6, pages 61–64. IEEE, Apr 2003.

[21] Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Uplink load estimation in wcdma. In *Proc. Wireless Communications and Networking Conference*, pages 1669–1674, New Orleans, USA, Mar 2003.

[22] Thomas Schön and Fredrik Gustafsson. Particle filters for system identification of state-space models linear in either parameters or states. In *Proceedings of the 13th IFAC Symposium on System Identification*, pages 1287–1292, Rotterdam, The Netherlands, Sep 2003.

[23] Ragnar Wallin, Anders Hansson, and L. Vandenberghe. Comparison of two structure-exploiting optimization algorithms for integral quadratic constraints. In *4th IFAC symposium on robust control design*, Milan, Italy, June 2003.

[24] Markus Gerdin, Torkel Glad, and Lennart Ljung. Parameter estimation in linear differential-algebraic equations. In *Proceedings of the 13th IFAC Symposium on System Identification*, pages 1530–1535. IFAC, Aug 2003.

[25] W. Scherrer and Fredrik Tjärnström. Connections between l_2-model reduction and balanced truncation. In *In Proceedings of the 13th Symposium on System Identfication*, pages FrP04–1, Rotterdam, The Netherlands, Sep 2003.

[26] Thomas Schön, Markus Gerdin, Torkel Glad, and Fredrik Gustafsson. A modeling and filtering framework for linear differential-algebraic equations. In *Proceedings of the 42nd Conference on Decision and Control*, Maui, HI, pages 892–897, Dec 2003.

[27] M. Nyström and Mikael Norrlöf. Path generation for industrial robots. In *Mekatronikmöte 2003*, Göteborg, Sweden, Aug 2003.

[28] Svante Gunnarsson, Mikael Norrlöf, E.Rahic, and M.Özbek. Iterative learning control of a flexible robot arm using accelerometers. In *Mekatronikmöte 2003*, Göteborg, Sweden, Aug 2003.

[29] Frida Gunnarsson, A. Björsson, B. Knutsson, Fredrik Gunnarsson, and Fredrik Gustafsson. Radio access network (utran) modeling for heterogenous network simulations, a brief description. In *First Swedish National Computer Networking Workshop*, Sep 2003.

[30] Fredrik Gustafsson and P. Hriljac. Particle filters for prediction of chaos. InIn *Proceedings of the 13th IFAC Symposium on System Identification*, Rotterdam, The Netherlands, Sep 2003.

[31] Anna Hagenblad, Fredrik Gustafsson, and Inger Klein. A comparison of two methods for stochastic fault detection: the parity space approach and principal component analysis. In *Proceedings of SYSID*, Aug 2003.

[32] Jonas Elbornsson and Fredrik Gustafsson. Analysis of mismatch noise in randomly interleaved adc systems. In *Proceedings of ICASSP*, Hong Kong, Apr 2003.

[33] Fredrik Gustafsson and Fredrik Gunnarsson. Positioning using time-difference of arrival measurements. In *Proceedings of ICASSP*, Hong Kong, Apr 2003.

[34] Rickard Karlsson and Fredrik Gustafsson. Particle filter and cramer-rao lower bound for underwater navigation. In *Proceedings of ICASSP*, Hong Kong, Apr 2003.

[35] Jonas Gillberg and Anders Hansson. Polynomial complexity for a nesterov-todd potential-reduction method with inexact search directions. In *Proceedings of thet 42nd IEEE Conference on Decision and Control*, page 6, Maui, Hawaii, USA, Dec 2003.

[36] Sun Ying, Fredrik Gunnarsson, and Kimmo Hiltunen. Cpich power settings in irregular wcdma macro cellular networks. In *Proc. IEEE Personal, Indoor and Mobile Radio Communications*, Beijing, P.R. China, Sep 2003.

[37] N. Wiberg, Hu Rong, Fredrik Gunnarsson, and B. Lindoff. Combining of power control commands during soft handover in wcdma. In *Proc. IEEE Personal, Indoor and Mobile Radio Communications*, Bejing, P.R. China, Sep 2003.

[38] Ola Härkegård. Resolving actuator redundancy - control allocation vs. linear quadratic control. In *Proc. of the European Control Conference*, Cambridge, UK, Sep 2003.

[39] Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Uplink load estimates in wcdma with different availability of measurements. In *Proc. Vehicular Technology Conference*, Jeju, Korea, Apri 2003.

[40] Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Adaptive filtering applied to an uplink load estimate in wcdma. In *Proc. Vehicular Technology Conference*, Jeju, Korea, Apr 2003.

[41] Fredrik Gunnarsson, David Törnqvist, Erik Geijer Lundin, G. Bark, N. Wiberg, and E. Englund. Uplink transmission timing in wcdma. In *Proc. IEEE Vehicular Technology Conference Fall*, Orlando, FL, USA, Oct 2003.

[42] D.Lawesson, U. Nilsson, and Inger Klein. Model-checking based fault isolation using automatic abstraction. In *Fourteenth International Workshop on Principles of Diagnosis (DX-03)*, pages 113–118, June 2003.

[43] D.Lawesson, U. Nilsson, and Inger Klein. Fault isolation using automatic abstraction to avoid state space explosion. In *Workshop on Model Checking and Artificial Intelligence (MoChArt-03)*, Aug 2003.

[44] Martin Enqvist and Lennart Ljung. Linear models of nonlinear fir systems with gaussian inputs. In *Proc. of the 13th IFAC Symposium on System Identification*, pages 1910–1915, Rotterdam, The Netherlands, Aug 2003.

[45] Ingela Lind and Lennart Ljung. Structure selection with ANOVA: Local linear models. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 51 – 56, Rotterdam, the Netherlands,, aug 2003.

[46] S.J. Qin and Lennart Ljung. Closed-loop subsapce identification with innovation estimation. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 887–892, Rotterdam, The Netherlands, Aug 2003.

[47] Lennart Ljung. Version 6 of the system identification toolbox. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 989 – 994, Rotterdam, The Netherlands, Dec 2003.

[48] P. Parrilo and Lennart Ljung. Initialization of physical parameter estimates. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 1524 – 1529, Rotterdam, The Netherlands, Aug 2003.

[49] Lennart Ljung. Educational aspects of identification software user interfaces. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 1590 –1594, Rotterdam, The Netherlands, Aug 2003.

[50] S. J. Qin and Lennart Ljung. Parallel QR implementation of subspace identification with parsimonious models. In S. Weiland P. van der Hof, B. Wahlberg, editor, *Prc. 13th IFAC Symposium on System identification*, pages 1631 – 1636, Rotterdam, The Netherlands, Aug 2003.

[51] Lennart Ljung. Aspects and experiences of user choices in subspace identification methods. In S .Weiland P. van der Hof, B. Wahlberg, editor, *Proc. 13th IFAC Symposium on System Identification*, pages 1802 – 1807, Rotterdam, The Netherlands, Aug 2003.

[52] Lennart Ljung. Initialisation aspects for subspace and output-error identification methods. In J. Maciejowski, editor, *Proc. European Control Conference, ECC 03*, Cambridge, UK, Sep 2003.

[53] Jacob Roll, A. Nazin, and Lennart Ljung. Local modelling with a priori known bounds using direct weight optimization. In *Proc. European Control Conference, ECC03*, Cambridge, Sep 2003.

[54] Jacob Roll, A. Nazin, and Lennart Ljung. Local modelling of nonlinear dynamic systems using direct weight optimization. In *13th IFAC Sym-*

posium on System Identification, pages 1554–1559, Rotterdam, Aug 2003.

[55] L. Vandenberghe, V. R. Balakrishnan, Ragnar Wallin, and Anders Hansson. On the implementation of primal-dual interior-point methods for semidefinite programming problems derived from the kyp lemma. In *Proceedings of the 42nd IEEE Conference on Decision and Control*, pages 4658–4663, Maui, Hawaii, USA, Dec 2003.

[56] Johan Löfberg. Approximations of closed-loop minimax MPC. In *Proceedings of the 42nd Conference on Decicion and Control*, Maui, HI, Dec 2003.

[57] D. Lawesson, U. Nilsson, and Inger Klein. Fault isolation in discrete event systems by observational abstraction. In *Proc of 42nd IEEE Conf on Decision and Control (CDC)*, Maui, Hawaii, Dec 2003.

[58] Svante Björklund and Lennart Ljung. A review of time-delay estimation techniques. In *42nd IEEE Conference on Decision and Control*, Hyatt Regency, Maui, Hawaii, Dec 2003.

[59] Christina Grönwall, T. Carlsson, and Fredrik Gustafsson. Performance analysis of measurement error regression in direct-detecting laser radar imaging. In *Proceedings of ICASSP. IEEE International Conference on Acoustics, Speech, and Signal Processing, 2003.*, volume 6, pages 545–548, Hong Kong, China, Apr 2003. IEEE.

Appendix H

Technical Reports

[60] Jacob Roll, A. Bemporad, and Lennart Ljung. Identification of piecewise affine systems via mixed-integer programming. Technical Report LiTH-ISY-R-2480, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[61] Jacob Roll. Robust verification of piecewise affine systems. Technical Report LiTH-ISY-R-2481, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[62] Jacob Roll, A. Nazin, and Lennart Ljung. A non-asymptotic approach to local modelling. Technical Report LiTH-ISY-R-2482, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[63] Jacob Roll, A. Nazin, and Lennart Ljung. Local modelling of nonlinear dynamic systems using direct weight optimization. Technical Report LiTH-ISY-R-2483, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[64] Jacob Roll, A. Nazin, and Lennart Ljung. Local modelling with a priori known bounds using direct weight optimization. Technical Report LiTH-ISY-R-2484, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[65] Jonas Elbornsson, Fredrik Gustafsson, and J.-E. Eklund. Blind adaptive equalization of mismatch errors in time interleaved a/d converter system. Technical Report LiTH-ISY-R-2486, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[66] Jonas Elbornsson, Fredrik Gustafsson, and J.-E. Eklund. Analysis of mismatch noise in randomly interleaved adc system. Technical Report LiTH-ISY-R-2487, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2003.

[67] Frida Gunnarsson, Fredrik Gunnarsson, and Fredrik Gustafsson. Issues on performance measurements of tcp. Technical Report LiTH-ISY-R-2491, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb 2003.

[68] Mikael Norrlöf. On path planning and optimization using splines. Technical Report LiTH-ISY-R-2490, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb 2003.

[69] Rickard Karlsson, Jonas Jansson, and Fredrik Gustafsson. Model-based statistical tracking and decision making for collision avoidance application. Technical Report LiTH-ISY-R-2492, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb 2003. Submitted to CDC 2003.

[70] Jonas Elbornsson, Fredrik Gustafsson, and J.-E. Eklund. Equalization of time errors in time interleaved adc system –part i: Theory. Technical Report LiTH-ISY-R-2494, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[71] Jonas Elbornsson, Fredrik Gustafsson, and J.-E. Eklund. Equalization of time errors in time interleaved adc system –part ii: Analysis and examples. Technical Report LiTH-ISY-R-2495, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[72] Jonas Elbornsson, Fredrik Gustafsson, and J.-E. Eklund. Analysis of mismatch effects in randomly interleaved a/d converter system. Technical Report LiTH-ISY-R-2496, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[73] Thomas Schön, Fredrik Gustafsson, and Anders Hansson. A note on state estimation as a convex optimization problem. Technical Report LiTH-ISY-R-2497, Department of Electrical Engineering, Linkï¿½ping University, SE-581 83 Linkï¿½ping, Sweden, Mar 2003.

[74] Thomas Schön, Markus Gerdin, Torkel Glad, and Fredrik Gustafsson. A modeling and filtering framework for linear implicit systems. Technical Report LiTH-ISY-R-2498, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[75] Dalius Navakauskas. Training algorithm for extra reduced size lattice-ladder multilayer perceptrons. Technical Report LiTH-ISY-R-2499, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[76] A. Usinskas and Dalius Navakauskas. Segmentation of ischemic stroke in ct images of human brain. Technical Report LiTH-ISY-R-2500, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[77] Ragnar Wallin, Anders Hansson, and L.Vandenberghe. Efficiently solving semidefinite programs originating from the KYP lemma using standard primal-dual solvers. Technical Report LiTH-ISY-R-2503, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[78] Ragnar Wallin, Anders Hansson, and L. Vandenberghe. Comparison of two structure-exploiting optimization algorithms for integral quadratic constraints. Technical Report LiTH-ISY-R-2502, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[79] R. Pupeikis, Dalius Navakauskas, and Lennart Ljung. Identification of wiener systems with hard and discontinuous nonlinearities. Technical Report LiTH-ISY-R-2501, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[80] M. Nyström and Mikael Norrlöf. Resultat från simuleringar av splinebaserade bangenereringsalgoritmer. Technical Report LiTH-ISY-R-2505, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[81] S. Paulikas and Dalius Navakauskas. Multirate implementation scheme for restoration of voiced speech signals. Technical Report LiTH-ISY-R-2508, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[82] R.Pupeikis, S.Paulikas, and Dalius Navakauskas. Recursive parameter estimation using closed-loop observations. Technical Report LiTH-ISY-R-2509, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar 2003.

[83] Jonas Gillberg and Anders Hansson. Polynomial complexity for a nesterov-todd potential-reduction method with inexact search directions: Examples related to the kyp lemma. Technical Report LiTH-ISY-R-2511, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[84] Anders Hansson, Anders Helmersson, and Torkel Glad. Stability analysis of nonlinear systems using frozen stationary linearization. Technical Report LiTH-ISY-R-2512, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[85] Markus Gerdin, Torkel Glad, and Lennart Ljung. Parameter estimation in linear differential-algebraic equations. Technical Report LiTH-ISY-R-2515, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[86] Markus Gerdin. Parameter identification in linear time invariant descriptor systems. Technical Report LiTH-ISY-R-2514, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[87] Svante Björklund. Experimental evaluation of some cross correlation methods for time-delay estimation in linear systems. Technical Report LiTH-ISY-R-2513, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[88] Johan Löfberg. Approximations of closed-loop minimax mpc. Technical Report LiTH-ISY-R-2516, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[89] Thomas Schön and Fredrik Gustafsson. Particle filters for system identification of state-space models linear in either parameters or states. Technical Report LiTH-ISY-R-2518, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[90] Ragnar Wallin. User's guide to $kypd_solver$. Technical Report LiTH-ISY-R-2517, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2003.

[91] W. Scherrer and Fredrik Tjärnström. Connections between l_2-model reduction and balanced truncation. Technical Report LiTH-ISY-R-2521, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, May 2003.

[92] Erik Wernholt and Måns Östring. Modeling and control of a bending backwards industrial robot. Technical Report LiTH-ISY-R-2522, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, May 2003.

[93] R.Pupeikis. Identification of piecewise affine wiener systems using data partition. Technical Report LiTH-ISY-R-2523, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, May 2003.

[94] Mikael Norrlöf and Svante Gunnarsson. A note on causal and CITE iterative learning control algorithms. Technical Report LiTH-ISY-R-2510, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jun 2003.

[95] R.Pupeikis. Iterative identification of wiener systems with discontinuous nonlinearities. Technical Report LiTH-ISY-R-, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jun 2003.

[96] Anders Helmersson. On synthesis of practically valid gain-scheduled controllers. Technical Report LiTH-ISY-R-2528, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jun 2003.

[97] Svante Björklund. Experimental evaluation of some thresholding methods for estimating time-delays in open-loop. Technical Report LiTH-ISY-R-2525, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jul 2003.

[98] Svante Björklund. Experimental evaluation of some methods using simple process models for estimating continuous time-delays in open-loop. Technical Report LiTH-ISY-R-2526, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jul 2003.

[99] Svante Gunnarsson, Mikael Norrlöf, E. Rahic, and M. Özbek. Iterative learning control of a flexible robot arm using accelerometers. Technical Report LiTH-ISY-R-2524, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jul 2003.

[100] M. Nyström and Mikael Norrlöf. Path generation for industrial robots. Technical Report LiTH-ISY-R-2529, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[101] Rickard Karlsson and Fredrik Gustafsson. Particle filter for underwater terrain navigation. Technical Report LiTH-ISY-R-2530, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[102] Frida Gunnarsson, A. Björsson, B. Knutsson, Fredrik Gunnarsson, and Fredrik Gustafsson. Radio access network (utran) modeling for heterogenous network simulations. Technical Report LiTH-ISY-R-2533, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[103] Svante Björklund. Analysis of a phase method for time-delay estimation. short version. Technical Report LiTH-ISY-R-2539, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2003.

[104] Per Spångéus and David Lindgren. Efficient parameterization for the dimensional reduction problem. Technical Report LiTH-ISY-R-2535, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[105] Frida Gunnarsson, Fredrik Gunnarsson, and Fredrik Gustafsson. Controlling internet queue dynamics using recursively identified models. Technical Report LiTH-ISY-R-2541, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2003.

[106] Svante Björklund. A study of the choice of model orders in arxstruc-type methods for open-loop time-delay estimation in linear systems. Technical Report LiTH-ISY-R-2536, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[107] M. Nyström and Mikael Norrlöf. PGT - a path generation toolbox for matlab (v0.1). Technical Report LiTH-ISY-R-2542, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2003.

[108] Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Uplink load estimates in wcdma with different availability of measurements. Technical Report LiTH-ISY-R-2544, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2003.

[109] Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Adaptive filtering applied to an uplink load estimate in wcdma. Technical Report LiTH-ISY-R-2545, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2003.

[110] Fredrik Gunnarsson, David Törnqvist, and Erik Geijer Lundin. Uplink transmission timing in wcdma. Technical Report LiTH-ISY-R-2546, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[111] D. Lawesson, U. Nilsson, and Inger Klein. Model-checking based fault isolation using automatic abstraction. Technical Report LiTH-ISY-R-2493, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb 2003.

[112] Erik Wernholt, S. Hanssen, S. Moberg, and Svante Gunnarsson. On the use of a multivariable frequency response identification method in the presence of periodic disturbances. Technical Report LiTH-ISY-R-2549, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[113] David Lindgren and Per Spångéus. A novel feature extraction algorithm for asymmetric classification ii. Technical Report LiTH-ISY-R-2550, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[114] Svante Björklund. Experimental open-loop evaluation of some time-delay estimation methods in the laguerre domain. Technical Report

LiTH-ISY-R-2537, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[115] Rickard Karlsson and Fredrik Gustafsson. Filtering and estimation for quantized sensor information. Technical Report LiTH-ISY-R-2552, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

[116] Jörgen Hansson, Anders Helmersson, Ragnar Wallin, Karin Ståhl-Gunnarsson, Fredrik Karlsson, and Anders Hansson. Clearance of flight control laws for time-varying parameters. Technical Report LiTH-ISY-R-2551, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Nov 2003.

[117] Torkel Glad and A. Sokolov. Structural identifiability: Tools and applications. Technical Report LiTH-ISY-R-2557, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[118] Lennart Ljung. Linear system identification as curve fitting. Technical Report LiTH-ISY-R-2466, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[119] L. L. Xie and Lennart Ljung. Estimate physical parameters by black box modeling. Technical Report LiTH-ISY-R-2463, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[120] Lennart Ljung. System identification and simple process models. Technical Report LiTH-ISY-R-2464, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[121] Lennart Ljung. Identification for control: Simple process models. Technical Report LiTH-ISY-R-2465, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[122] S. J. Qin and Lennart Ljung. Closed-loop subspace identification with innovation estimation. Technical Report LiTH-ISY-R-2559, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[123] S. J.Qin and Lennart Ljung. Parallel QR-implementation of subspace identification with parsimonious models. Technical Report LiTH-ISY-R-2563, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[124] P. Parrilo and Lennart Ljung. Initialization of physical parameter estimates. Technical Report LiTH-ISY-R-2561, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[125] Lennart Ljung. Version 6 of the system identification toolbox. Technical Report LiTH-ISY-R-2560, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[126] Lennart Ljung. Educational aspects of identification software user interfaces. Technical Report LiTH-ISY-R-2562, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[127] Lennart Ljung. Aspects and experiences of user choices in subspace identification. Technical Report LiTH-ISY-R-2564, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[128] Lennart Ljung. Initialisation aspects for subspace and output-error identification methods. Technical Report LiTH-ISY-R-2565, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[129] A. Nazin, Jacob Roll, and Lennart Ljung. A study of the dwo approach to function estimation at a given point: Approximately constant and approximately linear function classes. Technical Report LiTH-ISY-R-2578, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2003.

[130] David Lindgren. Subspace optimization techniques for classification problems. Technical Report LiTH-ISY-R-2534, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Aug 2003.

[131] Thomas Schön, Fredrik Gustafsson, and Per-Johan Nordlund. Marginalized particle filters for nonlinear state-space models. Technical Report LiTH-ISY-R-2548, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct 2003.

Appendix I

Master Theses (Examensarbeten)

[132] Klas Adolfsson. Tcp performance in an egprs system. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[133] Karl Ahlin. Quality of service in ip networks. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[134] Linus Alström. Algorithms for object detection in sar- and ir-images. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[135] Mattias Arnsby and Bo Tägtström. Modeling and control of the drive units in a forklift. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[136] Daniel Axehill and Johan Sjöberg. Adaptive cruise control for heavy vehicles - hybrid control and mpc. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[137] Anders Björsson. Simulation analysis of rlc/mac for umts in network simulator version 2. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[138] Per Connman and Oscar Öberg. System identification of non-linear electronic devices. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[139] Pär Degerman. Analysis and design of a redundant x-by-wire control system implemented on the volvo siriius 2001 concept car. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[140] Anders Ekman. Automatic measuring and detection of compromising emanations. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[141] Sofia Eriksson and Petter Isaksson. Model-based development of a roll angle indicator for motorcycles. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[142] Kenth Fredholm and Kristian Nilsson. Implementing an application for communication and quality measurements over umts network. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[143] Petter Frykman. Applied particle filters in integrated aircraft navigation. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[144] Roger Hamren and Martin Brandin. Classification of ground objects using laser radar data. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[145] Jörgen Hansson. Using linear fractional transformations for clearance of flight control laws. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[146] Per Holmberg. Sensor fusion with coordinated mobile robots. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[147] Fredrik Jansson and Oskar Johansson. A study of active engine mounts. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[148] Magnus Johansson. Model validation and robustness analysis of cold rolling mill. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[149] Erik Johnson. Development of control algorithms for electric power assisted steering. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[150] Staffan Jonson. Control of precision high speed milling for roll-to-roll applications. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[151] Jonas Kjellander. Positioning and mapping using range finding laser. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[152] Erika Lönnberg. Autonomous landing of a uav. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[153] Nawrous Mahmoud. A backstepping design of a control system for a magnetic levitation system. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[154] Erik Malmlöf and Ola Scholander. Control of flexible structures with multiple sensors. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[155] Richard Nilsson. Temperature control of aluminium extrusion process. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[156] Mårten Nygren. Improved speech communication in a car. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[157] Sara Nygårdhs. Aquaplaning - development of a risk pond model from road surface measurements. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[158] Maria Nyström. Pathgeneration for industrial robots. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[159] Stefan Nyström. Evaluation of a new method for extraction of drift-stable information from electronic tongue measurements. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[160] Jens Näsström. Volatility modelling of asset prices using garch models. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[161] Johan Odelius. Generation of probe signal for feedback cancellation systems. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[162] Andreas Olsson. Target recognition by vibrometry with a coherent lasar radar. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[163] Regina Rosander. Sensor fusion between a synthetic attitude and heading reference system and gps. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[164] Daniel Rosell. Modelling and simulation of the pressure control system in a nuclear power plant. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[165] Yvonne Sabbagh. Maximum likelihood estimation of hammerstein models. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[166] Conny Stenberg. Controllers with saturation. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[167] Albin Sunnanbo. Laser feedback control for robotics in aircraft assembly. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[168] Andreas Söderberg. Guidance laws for a hyper velocity missile. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[169] Jens Tornberg. Mpd waveforms for helicopter radar. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[170] Otto Tronarp. Quality of service in ad hoc networks by priority queuing. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[171] David Törnqvist. Transmission timing in wcdma terminals. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[172] Fredrik Vallin. Combining acoustic echo cancellation and suppression. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.

[173] Jonas Wiklander. Performance comparison of the extended kalman filter and the recursive prediction error method. Master's thesis, Department of Electrical Engineering, Linköping University, 2003.