# LINKÖPING UNIVERSITY
# DIVISIONS OF AUTOMATIC CONTROL AND COMMUNICATION SYSTEMS
# ACTIVITY REPORT
# 2005

# 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 a thousand students. The courses cover both traditional control topics and more recent topics in model building and signal processing. This report covers the activities of the division during 2005.

A major event during the year was that Fredrik Gustafsson was appointed to the chair and professorship of *Sensor Informatics*. His research group will be part of the Division of Automatic Control.

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.

### Funding

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 grant from SSF funds a research program VISIMOD, which is a joint program for research in Visualization, Modeling, System Identification, and Simulation. The participating groups are from the Departments of Electrical Engineering, Computer Science and from the Norrköping Visualization and Interaction Studio, NVIS. The program leader of VISIMOD is Lennart Ljung.

The VINNOVA Competence Center ISIS (Information Systems for Industrial Control and Supervision) formally completed its mission in December 2005, after 10 years of active cooperation between industry and several research groups a Linköping University. The automatic control group has been the largest research group in ISIS, and Lennart Ljung has been the Director of ISIS since the start in 1995.

The division is also a central partner in the Research School ECSEL (Excellence Center for Computer Science and Systems Engineering in Linköping), which started its activities during 1996. This research school is funded by the Foundation for Strategic Research (SSF) and is a joint effort between the departments of Electrical Engineering and Computer Science.

In December 2005 SSF decided to give a five-year support to a Strategic Research Center MOVIII with Lennart Ljung as Center Director. There will be more information about MOVIII in future annual reports.

### Some Highlights

During the year Gustaf Hendeby and Daniel Axehill defended their Lic. Eng. dissertations.

Ragnar Wallin, David Lindgren, Richard Karlsson, Jonas Jansson, Erik Geijer Lunding and Martin Enqvist all defended their Ph. D. dissertations during 2005

### Report Outline

In the following pages the main research results obtained during 2005 are summarized. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge, most easily from our web-site.

## Network Services

### Mail adresses

There are a number of ways you can access the work produced at this group. Most convenient is probably to email 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 forwarded to our secretary Ulla Salaneck.

Finally, you can also retrieve reports and software electronically using our World Wide Web services. This is our preferred method of distributing reports.

### World Wide Web

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

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

The competence center ISIS has the home page

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

The VISIMOD Research Program is described in

`http://www.ida.liu.se/zope/portals/visimod`

For the research school ECSEL turn to

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

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 have the opportunity to download technical reports produced at this group. This is the easiest way to access the group's work, just click and collect.

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# Chapter 2

# System Identification

## 2.1 Introduction

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

During 2005, two PhD theses, [1], and [4] have been finished in this area. These will be described in the next few sections. A third PhD thesis, [6] considers several aspects that are relevant to system identification.

## 2.2 Projection Techniques for Classification and Identification

David Lindgren's PhD thesis [4] concerns projection techniques for classification and identification purposes. Projections are used routinely in signal processing and multivariate data processing for estimation, compression, visualization and much more. Hence, it is important to have methods for finding and evaluating suitable projections.

Consider a problem setup where there are $q$ *classes* (or *populations*) and an *observation vector* that corresponds to an observation of one particular class. With this setup, the *classification* problem is how to determine which class the observation vector belongs to. Since this vector usually contains noisy measurements of the class properties, there will typically be a risk for errors in the classification process. Under some assumptions on the observation noise, the *Bayes error* provides a lower bound on the classification error rate.

The observation vector can have a very high dimension in some applications. In these cases, it can be desirable to try to find a suitable projection that reduces the size of the observations. However, since some information usually is lost in this procedure, a classification rule based on the projected observations will typically result in a higher Bayes error. The problem of finding a projection that minimizes Bayes error, or some approximation of it, is studied in David Lindgren's thesis. Methods for approximating Bayes error as well as numerical methods for finding the optimal projection with respect to these approximate accuracy measures are investigated. The Bayes error approximations are based on the *Mahalanobis* and *Bhattacharyya distances*, and the subspace gradients of these approximations are derived and used in the numerical optimization. Different numerical optimization techniques specialized for searching for optimal projections or subspaces have been evaluated. These techniques are based on *Givens rotations*, *Householder reflections*, *steepest descent* or *nonlinear conjugate gradients methods*. The conclusion is that the nonlinear conjugate gradient method on the *Grassmann manifold* is one of the most time efficient numerical optimization methods to use with this type of problems. Furthermore, it is shown how the Bayes error optimal one-dimensional projection for two concentric classes with different covariance matrices can be found by solving a generalized eigenvalue problem.

Another topic that is discussed in the thesis is *quantification*. Quantification is similar to classification in the sense that a measurement $x_t$ that is associated with some scalar quantity $y_t$ should be used to determine the unknown quantity. However, unlike the case in classification, $y_t$ is continuous in quantification. A quantification problem consists of two subproblems, a *calibration* and an *operation* problem. In the calibration problem, the quantity $y_t$ is known and the corresponding $x_t$ is measured. The task is to obtain a model of the relation between $x$ and $y$ based on $N$ measurements $\{y_t, x_t\}_{t=1}^{N}$. In the operation problem, $x_t$ is measured and the unknown quantity $y_t$ is estimated. Projection techniques can be useful in quantification problems where the noise-free part of the $n$-dimensional $x$-measurements only span a subspace of $\mathbb{R}^n$. In the thesis, calibration modeling using both *classical* and *inverse regression* is studied. Furthermore, a method for finding quantification projections, which is based on the assumption that there is a natural clustering in the quantification data, is proposed.

Many methods for identification of nonlinear dynamical systems suffer from the curse of dimensionality. In some cases, low-dimensional data projections might be a way to circumvent this problem. In David Lindgren's thesis, it is shown that a criterion based on *Delaunay triangulation* can be used to evaluate projections for nonlinear dynamical systems. The idea is to minimize a criterion that is related to the volume of the Delaunay triangles defined by the projected dataset and to use the fact that this volume will be small if a suitable projection has been used.

An alternative approach for obtaining projections for data from dynamical systems is to use methods for estimation of *multi-index models*. Consider a nonlinear auto-regressive system with external input (a NARX system) that can be written

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

where the regression vector $\varphi(t)$ contains past input and output components and where $e(t)$ is measurement noise. Assume that the nonlinear function $f$ can be written

$$f(\varphi(t)) = b^T\varphi(t) + g(S^T\varphi(t)),$$

where $S$ defines a low-dimensional projection of the original regression vector. This particular structure is known as a multi-index model structure. In the thesis, it is shown that multi-index models can be fitted to data from dynamical systems by iteratively estimating either $b$ and $g$ or $S$. These results are described also in [56]

A visualization method based on advanced volume graphics that can be used as a support tool for system identification is presented in the thesis and in [50]. This method can be used for detection of nonlinearities and time varying dynamics.

## 2.3 Linear Models of Nonlinear Systems

The focus of Martin Enqvist's PhD thesis [1] is on linear time-invariant (LTI) approximations of nonlinear systems. Such approximations are used in many applications and can be obtained in several ways. For example, using system identification and the prediction-error method, it is always possible to estimate a linear model without considering the fact that the input and output measurements in many cases come from a nonlinear system. The main objective of Martin Enqvist's thesis is to explain some properties of such approximate models.

More specifically, LTI models that are optimal approximations in the sense that they minimize a mean-square error criterion are considered. These models define the asymptotic properties of models obtained by the prediction-error method when the number of measurements tends to infinity. The optimal linear output-error (OE) model $G_{0,OE}(q)$ of a system with input signal $u(t)$ and output signal $y(t)$ is defined as

$$G_{0,OE}(q) = \arg\min_{G \in \mathcal{G}} \mathrm{E}((y(t) - G(q)u(t))^2),$$

where $\mathcal{G}$ denotes the set of all stable and causal LTI models and where E denotes expected value. This model is called the OE LTI Second Order Equivalent (OE-LTI-SOE) since it is an equivalent to the true system with respect to some second order properties of the input and output signals. Furthermore, the corresponding optimal LTI model with a noise model, which is called the General Error LTI-SOE (GE-LTI-SOE), is also defined and analyzed in the thesis.

Some interesting, but in applications usually undesirable, properties of OE-LTI-SOEs and GE-LTI-SOEs are pointed out. It is shown that the optimal linear models can be very sensitive to small nonlinearities. Hence, the linear approximation of an almost linear system can be useless for some applications, such as robust control design. Furthermore, it is shown that standard validation methods, designed for identification of linear systems, cannot always be used to validate an optimal linear approximation of a nonlinear system.

In order to improve the models, conditions on the input signal that imply various useful properties of the linear approximations are given in the thesis. It is shown, for instance, that minimum phase filtered white noise in many senses is a good choice of input signal. Models obtained with such an input signal exhibit a particular optimality property and can be validated with spectral and residual analysis, just like in the linear case. These results are described also in [33] and [70].

The class of separable signals is studied in detail in Martin Enqvist's thesis. A stochastic signal $u(t)$ is separable if

$$\mathrm{E}(u(t-\tau)|u(t)) = a(\tau)u(t), \quad \forall \tau \in \mathbb{Z},$$

where $a(\tau)$ is some function that does not depend on $u(t)$. Separability of the input signal is a necessary and sufficient criterion for the OE-LTI-SOE


Figure 2.1: A generalized Wiener-Hammerstein system.

of a static nonlinearity always to be a constant. It turns out that random multisine signals where all amplitudes are equal are separable.

The notion of separability can be generalized to nonlinear finite impulse response (NFIR) systems

$$y(t) = f((u(t-k))_{k=0}^{M}) + w(t).$$

The OE-LTI-SOE of such a system is always a linear finite impulse response (FIR) system with the same impulse response length if and only if the input signal is separable of order $M+1$, i.e., if the input satisfies

$$\mathrm{E}\big(u(t-\tau)|u(t), u(t-1)\ldots, u(t-M)\big) = \sum_{i=0}^{M} a_i(\tau)u(t-i), \quad \forall \tau \in \mathbb{Z},$$

where $a_i(\tau)$ are functions of $\tau$ that do not depend on the $u$ components. Gaussian signals are separable of any order and it turns out that these signals are especially useful for obtaining approximations of generalized Wiener-Hammerstein systems. These systems are a natural generalization of Wiener-Hammerstein systems and their structure is shown in Figure 2.1. Many of the results about higher order separability have been published also in [11] and [72].

Furthermore, some theoretical results about almost linear systems are presented in the thesis. For example, a result about the uniform convergence of OE-LTI-SOEs for a large set of input signals when the size of the nonlinearities in a system tends to zero is presented. Approximations of almost linear NFIR systems are also analyzed.

In standard methods for robust control design, the size of the model error is assumed to be known for all input signals. However, in many situations, this is not a realistic assumption when a nonlinear system is approximated with a linear model. In Martin Enqvist's thesis, it is described how robust control design of some nonlinear systems can be performed based on a discrete-time linear model and a model error model valid only for bounded inputs. This is a special case of the approach presented in [41] and [83].

It is sometimes undesirable that small nonlinearities in a system influence the linear approximation of it. In some cases, this influence can be reduced if a small nonlinearity is included in the model. In the thesis, an identification method with this option is presented for nonlinear autoregressive systems with external inputs. Using this method, models with a parametric linear part and a nonparametric Lipschitz continuous nonlinear part can be estimated by solving a convex optimization problem [59, 94].

## 2.4 Structure Selection in Nonlinear Models

An important part of nonlinear black-box system identification is to select an appropriate model structure. This includes finding which regressors are relevant, a problem known as regressor selection.

The paper [19] investigates how ANOVA can be used for the purpose of regressor selection for nonlinear dynamical systems. It is demonstrated that ANOVA is much faster than using, e.g., neural networks, and typically also more reliable, even if the ideal conditions for which ANOVA was designed are typically violated in system identification applications. In [55], it is shown how one can also distinguish between linear and nonlinear dependencies of a regressor, by applying ANOVA to the residuals from a linear model fitted to the data.

Nonlinear systems may contain multiplicative terms between the input, output and noise. In general, the terms associated with noise need to be modelled to obtain unbiased parameter estimates, significantly increasing the number of candidate terms to be estimated. In [18] a special case is considered, where it is possible to use an output error model structure and an instrumental variable estimator to obtain unbiased parameters without modelling the noise, thus significantly reducing the dimensionality of the problem.

## 2.5 Estimation of Continuous-time Models

Identification of continuous-time systems can be motivated by the fact that most physical modeling takes place in this domain. Some results about estimation of continuous-time output error models based on sampled data are presented in [40]. The exact solution to this problem can be found in literature, but might be too complicated for some applications, in particular in the case of non-uniformly sampled data. Because of this, various ways to approximate the exact method for reasonably fast sampling are presented.

Direct identification of continuous-time autoregressive moving average noise models is the topic of [39]. The used approach originates in the frequency domain Whittle likelihood estimator. The discrete- or continuous-time spectral densities are estimated from equidistant samples of the output. For low sampling rates, the discrete-time spectral density is modeled directly by its continuous-time spectral density using the Poisson summation formula. In the case of rapid sampling, the continuous-time spectral density is estimated directly by modifying its discrete-time counterpart.

A frequency domain approach to continuous-time auto-regressive (AR) signal modeling is proposed in [38]. Unlike conventional AR modeling in the time domain, this approach allows for data pre-filtering.

## 2.6 Nonlinear System Identification via Direct Weight Optimization

For nonlinear systems, it may sometimes be difficult to find a parametrized model class that is able to accurately describe the system dynamics, and hence a local, nonparametric regression method can be an attractive choice. Direct Weight Optimization (DWO) [23] is such a method, that estimates the system dynamics function $f$ for each specific regression vector $\varphi^*$, i.e., an estimate of $f(\varphi^*)$ is found. This is done by minimizing an upper bound on the worst-case mean-square error. In order to get such an upper bound, something must be known *a priori* about the function $f$. In the original formulation of DWO, presented in [23], it is assumed that a Lipschitz bound for the derivative of $f$ is known. This framework is generalized in [60], to include a variety of different function classes.

## 2.7 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. We have reported on several aspects of subspace methods in earlier annual reports. A specific aspect is that subspace methods usually fail with closed loop data. A modification that takes care of that problem is described in [54]. The idea is to make an estimate of the innovations sequence, in order to avoid the correlation between past innovations and the input. That contribution also contains a comparison of various approaches to this problem.

Another aspect of subspace methods is that the “long” ARX models that form the basis for the state construction are not forced to be causal in the standard algorithms. Forcing these models to be causal takes some extra effort but leads to the estimation of fewer parameters and thus gives a potentially more efficient estimate. Such an approach is described in [21].

## 2.8 Miscellaneous

### 2.8.1 Applications to Robotics

Several applications to identify industrial robot dynamics have been made during the year. These are described in Section 7.2.

### 2.8.2 Filtering for DAE Models

A first step in estimating models that are described by differential algebraic equations (DAE-models) is to correctly handle state estimation for such models. This involves some hidden problems, in that the noise sources may be improperly handled in that process – differentiation of white noise sources is not a well posed procedure. Various aspects of the filtering problem for DAE model are discussed in [37].

### 2.8.3 Time Jitter

An application to identification of time jitter effects for sensor measurements with randomly varying time stamps is described in Section 4.5

### 2.8.4 Biological applications

In [35], the dynamics of the cell cycle of yeast cells is studied. In particular, the paper discusses a method for separating linear from nonlinear dynamics, based on comparison of different linear models, identified over different time intervals.

# Chapter 3

# Nonlinear Systems

## 3.1 Control allocation

Control allocation deals with the problem of distributing a given control demand among an available set of actuators. It can be posed as a quadratic minimization problem which distributes the control effort among the actuators. In [15] this technique is extended to nonlinear systems. The actuator redundancy management for a class of overactuated nonlinear systems is examined. Two tools for distributing the control effort among a redundant set of actuators are considered, namely optimal control design and control allocation. The relationship between these two design tools are investigated when the performance indices are quadratic in the control input. It is shown that for a particular class of nonlinear systems, they give exactly the same design freedom in distributing the control effort. Linear quadratic optimal control is contained as a special case. A benefit of using a separate control allocator is that actuator constraints can be considered, which is illustrated with a flight control example.

## 3.2 DAE models

### 3.2.1 Well-posedness of models

General approaches to modeling, for instance using object-oriented software, lead to differential algebraic equations (DAE), also called implicit systems or descriptor syatems. 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). This might lead to mathematical difficulties because of hidden differentiation of the signals. In [37] it is discussed how such problems can be detected and avoided.

### 3.2.2 Identification

The identification of DAE models poses challenges because the model is not in the standard form required by much identification software.

When estimating unknown parameters, it is important that the model is identifiable so that the parameters can be estimated uniquely. For nonlinear differential-algebraic equation models with polynomial equations, a differential algebra approach to examine identifiability is available. This approach can be slow, but [78] describes how this method can be modularized for object-oriented models. A characteristic set of equations is computed for components in model libraries, and stored together with the components. When an object-oriented model is built using such models, identifiability can be examined using the stored equations.

Another approach, described in [77], uses solvers for differential-algebraic equations to examine if a model structure is locally identifiable. The procedure can be applied to both linear and nonlinear systems. If a model structure is not identifiable, it is also possible to examine which functions of the parameters are locally identifiable.

There are interesting connections between solvability analysis of DAE equations and classical observability theory. In [76] these connections are examined and it is shown that they give an alternative way of deriving classical observability tests for nonlinear systems. This framework can also easily accomodate tests of identifiability. The criteria are based on rank tests.

### 3.2.3 Optimal Control

Feedback solutions of optimal control problems can be computed from the Hamilton-Jacobi equation. A classical way of doing this uses series expansions. In [62] it is shown how a series solution to optimal control problems for DAE models can be calculated. It turns out to be possible to calculate a solution directly from the DAE model without first transforming it to state space form.

## 3.3 Robustness and model error models

Much attention in robust identification and control has been focused on linear low order models approximating high order linear systems. A more realistic situation, described in [41] is a linear model approximating a non-linear system. For this situation a non-linear model error model can be developed. The validity of such a model is typically restricted to input signals that are limited in amplitude. It is then natural to require the same amplitude restriction when designing controllers. The resulting implications for controller design are investigated in both the continuous and the discrete time case.

## 3.4 Control of rigid bodies

Control of rigid body motion is an important part of many control problems. As a first step in the study of such control problems, a classical example, the tippe.topp is considered. In [22] the asymptotic motions are investigated using Jellet's integral and Lyapunov type arguments. A complete characteriazation of the asymptotic motions in terms of the problem parameters is achieved.

# Chapter 4

# Sensor fusion

## 4.1 Main events

Highlights of the year are

- The doctoral thesis of Rickard Karlsson [3] and Jonas Jansson [2].
- The licentiate thesis of Gustaf Hendeby [8].
- The surveys [14, 47].

## 4.2 Project overview

- **Particle filtering.** The theoretical research focuses on obtaining scalable and real-time algorithms for sensor fusion applications, where marginalization is the key tool, see [24].
  *Fundings:* Swedish Research Council (VR).

- **Sensor fusion applications.** The vision and mission is to position everything that moves. We have applications to aircraft, cars (see next area below), surface ships, underwater vessels, film cameras, cellular phones and industrial robots. One leading theme is to consider cameras and Geographical Information Systems (GIS) as standard sensors in sensor fusion. A technical driver is to backup, support or replace GPS in critical integrated navigation systems. In some cases, the (Extended) Kalman filter is used in our application, but in particular when GIS are used, the particle filter and marginalized particle filter mentioned above are applied.

*Fundings:*

- Swedish Research Council (VR).
- MOVIII (SSF)
- Marker-less augmented reality Matris (EU FP5) (positioning film cameras).
- Linklab: navigation of UAV's.
- FOI: Institution for laser systems (positioning ground targets).

- **Sensor fusion for automotive safety systems** is a central activity at the sensor fusion group, see the survey [47].
*Fundings:* Two IVSS (Intelligent Vehicle Safety Systems) projects:
  - Systems for Collision Avoidance
  - Sensor Fusion Systems (SEFS)
  - Long-term collaboration with Volvo Car and Nira Dynamics AB.

- **Sensor networks.** The research concerns localization in wireless networks, and fundamental limitations with particular focus to the US legislations for cellular phones, see [14].

## 4.3 Theory overview

We will here describe the general area of sensor informatics. We split the *sensor informatic problem* into

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

The reason for the latter is that it 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

| | | | |
|---|---|---|---|
| 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 4.1: *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 4.5. 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 4.4.*

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 1993 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 4.1 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 4.1, 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.

## 4.4 Sensor fusion projects

The current projects include

- The marginalized particle filter is thoroughly described in [24]. As a general tool, it has the potential of increasing estimation accuracy and reducing computational complexity at the same time. Complexity issues are analyzed in [17, 14].

- Positioning of robot tools, [53]. Using accelerometers at the tool of a robot and sensor fusion techniques, the accuracy of tool positioning can be increased.

- Fundamental limitations in filtering. What is the ultimate accuracy that can be achieved given infinite computational and memory resources? The Cramér-Rao lower bound gives once such accuracy bound for the second order moment. For linear systems with non-Gaussian noise, the Kalman filter is the linear filter that provides the best second order accuracy, but non-linear filters as the particle filter may give much better performance. In [8, 49], explicit results are given for this case.

- Underwater navigation using terrain databases is presented in [52]. Basically, the problem and solution is the same as for aircraft terrain navigation, see Figure **??**. The contribution here is a dedicated analysis and algorithm, with intuitive Cramer-Rao bound expressions for how good the performance might be.

- The particle filter for quantized measurements is derived in [51].

- Target tracking using bearings-only measurements is treated in [16]. Here, also the fusion with Geographical Information Systems is described.

- Positioning of cellular phones is investigated in [13]. In particular, time difference of arrival (TDOA) measurements promise good positioning in current and future standards. We have derived fundamental limitations for positioning (snap-shot) as well as filtering (trajectory), and compared these to the US FCC rules.

- Cramer-Rao analysis in laser radar imaging systems is presented in [42].

## 4.5 Non-uniform sampling

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, in Figure 4.1, 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. Partial results of how to estimate the jitter, and reconstruct a uniformly sampled signal appeared in [10].

- Stochastic sampling jitter occurs when time stamps of sensor measurements have unknown random errors. This occurs for instance in some communication protocols as CAN in vehicles and in high-speed applications where clock synchronization in not perfect. Theory of frequency analysis based on samples subject to stochastic jitter is developed in in [31, 32].

- System identification based on non-uniform samples with known sampling instants, is treated in [38].

## 4.6 Automotive collision avoidance

An automotive collision avoidance system incorporates many important sensor fusion aspects:

- Navigation for ego-motion estimation.

- Target tracking for situational awareness.

- Road prediction for hazard evaluation.

- Decision support.

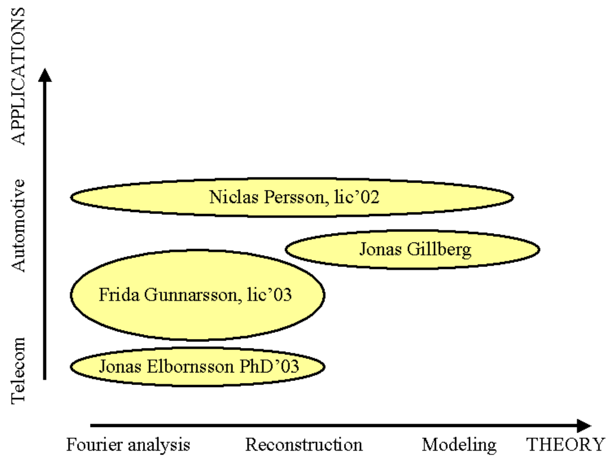


Figure 4.1: Previous research projects in non-uniform sampling

The challenge is to design these in a system showing an extremely low false alarm rate and good intervention performance. Our collaboration with Volvo Car Corp has given valuable knowledge, which has been substantiated in several demonstrator vehicles that have been tested extensively with successful result. The publications this year include the following projects:

- A sensor fusion framework for all three tasks of navigation, tracking and road prediction. This includes a curved coordinate system following the road [30], where the host vehicle's and tracked vehicles' lateral positions are given as deviations from the reference lane. In this way, all relevant parameters are collected in one state vector, where sensor inputs from own intertial sensors and wheel speeds are mixed with radar, lidar, IR and vision information in a common measurement model.
- A lane keeping aid system is described in [30].
- A collision mitigation by braking system is developed in [2]. This includes aspects as stochastic uncertainty for decision support and multi-target situational awareness.

# Chapter 5

# Detection and Diagnosis

## 5.1 Robust fault detection

The Generalized Likelihood Ratio (GLR) test for fault detection as derived by Willsky and Jones is a recursive method to detect additive changes in linear systems in a Kalman filter framework. Robust fault detection is defined as being insensitive to faults in the signal space, and this has been studied in the GLR framework. In [103, 63] the GLR test is evaluated on a sliding window and compared to stochastic parity space approaches. The work concerns primarily linear Gaussian models where arbitrary fault vectors are considered, including incipient faults (slowly increasing) and general time-varying fault profiles. Cases were slowly moving faultprofiles are present is also covered by the use of Chebyshev polynomes as basis for the fault. The advantage here is that the dimension of the fault vector is lower. The GLR approach maximizes the likelihood ratio function over all faults, and the explicit GLR test statistic is developed. It turns out that this in both hypotheses tests can be expressed as a certain projection of the residual.

A second approach is to estimate the state rather than projecting the residual to the parity space.

The methods above have been applied to disturbance detection on an Inertial Measurement Unit, IMU. An IMU contains of gyroscopes, accelerometers and magnetometers (compass), all in three dimensions. The problem with these devices is that the magnometers are easily disturbed by ferromagnetic objects. The model for an IMU is nonlinear, but has been locally linearized to fit our framework.

## 5.2 Fault detection in linear Non-Gaussian Systems

Sophisticated fault detection (FD) algorithms often include nonlinear mappings of observed data to fault decisions, and simulation studies are used to support the methods. Objective statistically supported performance analysis of FD algorithms is only possible for some special cases, including linear Gaussian models. The goal here is to derive general statistical performance bounds for any FD algorithm, given a nonlinear non-Gaussian model of the system. Recent advances in numerical algorithms for nonlinear filtering indicate that such bounds in many practical cases are attainable. Here we focuse on linear non-Gaussian models. A couple of different fault detection setups based on parity space and Kalman filter approaches are considered, where the fault enters a computable residual linearly. For this class of systems, fault detection can be based on the best linear unbiased estimate (BLUE) of the fault vector. Alternatively, a nonlinear filter can potentially compute the maximum likelihood (ML) state estimate, whose performance is bounded by the Cramér-Rao lower bound (CRLB). The contribution in this paper is general expressions for the crlb for this class of systems, interpreted in terms of fault detectability. The analysis is exemplified for a case with measurements affected by outliers. [48, 86, 8]

# Chapter 6

# Communication Applications

## 6.1 Introduction

In the third generation cellular radio systems, the available resource is not fixed, but flexible and depend critically on the network deployment. The wireless communication system comprises many algorithms which have to be implemented in a distributed fashion but mutually affect each other. Also the information is distributed, and full observability of the system behavior is almost always not possible. Therefore, careful design and analysis of the various algorithms is crucial.

The communication applications projects are carried out in cooperation with Ericsson Research. The aim is to apply methods from control theory and signal processing to algorithms on different layers in wireless communications systems.

One instructive approach is to separate the resource management in two segments:

- Radio resource management. This segment focuses on the radio access network to enable efficient transport of data from transmitters to receivers. Aspects, such as efficiency, feasibility, stability, fairness etc are central.

- Data network control. The data over the links is not continuous, and its flow depend on the behaviour of the core network run by the operator, and of other Radio network connected to a core network and the Internet connected networks, such as the Internet. The data flow depends on both end-to-end transport protocols and on flow control mechanisms in nodes.

## 6.2 Radio Resource Management

The highlight of the year was the doctoral thesis "Uplink Load in CDMA Cellular Radio Systems" by Erik Geijer Lundin [5].

A prerequisite for proper behavior of radio network algorithms is that not more users than actually can be served are admitted into the system. This is of course intuitive, but with limited observability rather difficult to ensure. The situation is especially hard in the uplink communications from mobiles to the base stations, since the system has no absolute control of the transmitter powers $p_i$ of the mobiles. These depend in turn on the radio propagation conditions from mobile $i$ to base station $j$, $g_{ij}$, which are subject to rapid changes, and the received radio signal quality in terms of *carrier-to-total-interferece-ratio* (CTIR) $\beta_i$. Each mobile contribute $Ci, *$ to the total received power both to the set of connected base stations $K_i$, which can control the mobile to some extent, and to all other base stations, which cannot control the mobile. This is illustrated by Figure 6.1. A common measure

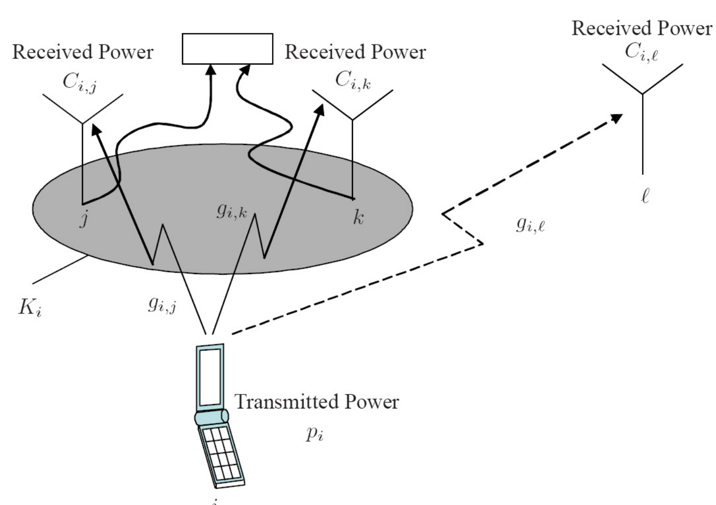


Figure 6.1: Radio access network with a mobile connected to an active set of base stations, and contribution to the interference in all base stations.

of the uplink load is the noise rise $\Lambda_j$, which is the ratio between the total received power $I_j^{tot} = \sum_i C_{i,j} + N_j$ and the backround noise $N_j$. Furthermore since the connections mutually affect each other, it is important there exists a power allocation that supports the requirements of all users in terms of $\beta_i$, i.e. that the power control problem is *feasible*.

Several authors have stressed the soft capacity property of CDMA systems, where the capacity depend on the radio conditions of the connections, in contrast to hard capacity, where the amount of resources are fixed. Furthermore, it is instructive to discuss the soft capacity in terms of the relative load, i.e. relative a max capacity. The research is based on two different relative load measures:

- *Noise rise relative load* $L_j^{nr}$ based on the pole equation

$$\Lambda_j = \frac{1}{1 - L_j^{nr}}$$

- *Feasibility relative load* $L_j^f$ is based on the feasibility property of the power control problem, and it describes the relation between the current load and the load at which the power control problem becomes infeasible.

Since the connections mutually affect each other, the relations between noise rise, CTIR and radio conditions are non-linear, approximations and fix-point iterations are employed to estimate noise rise. The properties of the approximations are analyzed, and it is proved that they serve as tight bounds for the noise rise relative load and the feasibility relative load. Furthermore, point iterations of approximations converge given a feasible system, and the convergence point is the noise rise relative load under certain conditions [5, 58].

The step from the uplink load properties described above, to uplink load control is natural. The main challenge is limited information. Either the control algorithm is hosted in a central node and then receives limited information from a wide area. Or, the algorithm is located in a local node (base station) and then has only good knowledge of the situation in the corresponding cell. The proposed suite of load control algorithms [57, 93] uses decisions made both in a central node and in the base stations. The central node, operating on a slow update rate, guarantees system stability and controls the resource pool to provide resource usage restrictions to the base stations. In addition, the base stations can make fast decisions to improve performance based on rapid changes in the local radio environment, while following the resource restrictions from the central node. In detail, the central node uses a utility function to handle the trade-off between maximizing the total resources and providin fairness, and the solution to the convex optimization problem gives constraints distributed to the base station, which in turn optmizes the resource allocation between connected users.

In essence, load control is about keeping the uplink interference under control. This is particularly challenging when users are allocated high bit rates. It is also of interest to study the coexistence behavior of traditional real-time services and best-effort high bit rate users using evolved 3G. These aspects are investigated in the Masters Theses [106, 107].

Related is also the work on more advanced base station receivers. Uplink interference cancellation is considered as a means to handle highly loaded base station. This will lead to consequences for radio resource management and the system capacity as was elaborated upon in [43]. It also is described how a given interference reduction can result in either a capacity gain or a coverage gain, which were derived.

The optimal solution to the multiuser detection problem is intractable in practice. Instead, various suboptimal solutions are discussed. One approach is to formulate multiuser detection as a maximum likelihood problem, which leads to a binary quadratic programming problem. The pseudo-random sequences used in CDMA gives low correlation between two different connections. This fact can be exploited in a preprocessing algorithm, which is capable of detecting most users, and significantly reducing the complexity [26, 66].

## 6.3 Data Network Control

Many people consider 3G as the technology that makes Internet generally available to mobile users. This means that the fields of telecommunications and data communications will overlap to a greater extent than before. While the paradigm in data communications is flexibility, the key word within telecommunications is efficiency of the wireless link. Therefore, some flow control mechanisms used of wired Internet causes problems when used directly over wireless links.

In order to study the impact from modifications to queue management etc in combined fixed and wireless networks, additions to the network simulator *ns-2* has been made. The Master Thesis [143] investigates the performance of evolved 3G including High Speed Downlink Packet Access (HSDPA) including protocols and varying radio conditions.

Proper queue management is not only important in the radio access network, but also in the transport network conncting the nodes in the network. The Master Thesis [110] considers a control theory approach to flow control in the transport network to be used in evolved 3G and HSDPA.

## 6.4 Related Work

Some work bridges the reasearch projects. Positioning in wireless communication networks is one example where a sensor fusion approach is used to address the problem [13]. Since nonlinearities and non-Gaussian noise are present, the particle filtering framework is plausible.

# Chapter 7

# Robotics

## 7.1 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.

## 7.2 Identification of Industrial Robots

An industrial robot represents a challenging task for system identification since it is a multivariable, nonlinear system operating in closed loop. One sub-problem is to identify physically parameterized models at joint level, including the motor and the gear box. Such models have to include several nonlinear phenomena, such as nonlinear stiffness of the mechanical flexibility and nonlinear friction. The work presented in [65] deals with identification of nonlinear stiffnes. Using a three step procedure, where the first two steps are used to determine suitable initial values of the parameters, it is shown how the nonlinear stiffnes can be identified.

When collecting data from industrial robots the signals are often sampled using the sampling frequency of the robot control system itself. For identification purposes this often implies unnecessarily high sampling rate. In [44] it is studied how the use of decimation affects the identification result, and it is illustrated that decimation in combination with an assumption about zero order hold input can give unrealistic parameter estimates.

## 7.3 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 7.1 where the output of the ILC algorithm is $u_{k+1}(t)$ defined for $0 \leq t \leq t_f$.

Mathematically the algorithm can be 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. In [20] some fundamental limitations of causal and *Current Iteration Tracking Error* (CITE) discrete time ILC algorithms are studied using time and frequency domain convergence criteria. Of particular interest are conditions for monotone convergence, and these are evaluated using a discrete time version of Bode's integral theorem. A relation between the frequency domain convergence conditions and the time-domain monotone convergence criterion is also discussed.

## 7.4 Sensor integration

Modern industrial robot control is usually based only upon measurements from the motor angles of the manipulator. The ultimate goal however is to

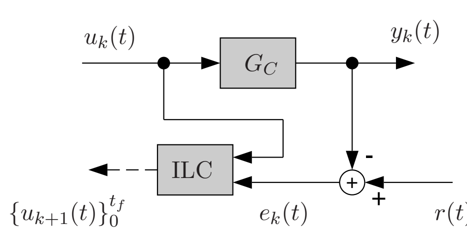


Figure 7.1: An example of a system controlled using ILC.

make the tool move according to some predefined path. A possible configuration where sensor integration could be used is shown in Figure 7.2 where a robot equipped with a 3-axes accelerometer is depicted.

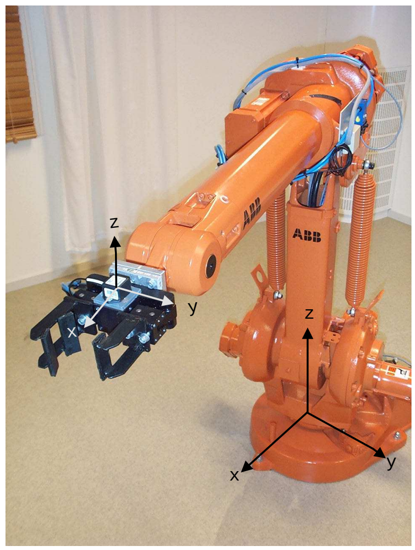


Figure 7.2: An ABB IRB1400 robot with a 3-axes accelerometer mounted on top of the gripper.

The Bayesian estimation techniques have been applied to a realistic flexible robot model in [53, 91]. In [91] it is shown that the arm position, velocity, and acceleration estimates can be improved by using sensor fusion with arm acceleration measurements in combination with the motor positions. [91] covers an *Extended Kalman Filter* (EKF) solution as well as a one using the *Particle Filter* (PF). In an extensive simulation study on a realistic flexible industrial robot, the performance is shown to be close to the fundamental Cramér-Rao lower bound. A significant improvement in position accuracy is achieved using the sensor fusion technique and the method is also proven to be robust to parameter variations in the model. In [53] modeling aspects are stressed and the sensitivity to parametric model errors is investigated.

## 7.5 Control

In [36] a gain scheduling control of a nonlinear system is presented. It is assumed that the reference trajectory is given in advance. Multiple frozen operating times are chosen on the reference trajectory and a linear time invariant model is obtained at each operating time. A linear parameter varying model is then constructed by interpolating the region between the neighboring frozen operating times. A gain scheduling state feedback law is designed by a linear matrix inequality formulation. The effectiveness is demonstrated in a numerical simulation of a tracking control of a two-link robot arm.

# Chapter 8

# Optimization for Control and Signal Processing

## 8.1 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, for model predictive control and for the multiuser detection problem.

## 8.2 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 decomposition algorithms. This work has been presented in [64].

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. 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 more detail in Ragnar Wallin's dissertation, [6]. 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 is described in [64].

## 8.3 Model Predictive Control

Model Predictive Control (MPC) has proven to be very useful in process control applications. Efficient optimization routines to be used on-line is an active area of research. In recent years the interest in controlling so-called hybrid dynamical systems has increased. Hybrid dynamical systems are systems with both continuous and discrete components. They are useful, e.g., when modeling systems containing logics, binary control signals or when approximating non-linear systems as piecewise linear systems. When MPC is used for control of hybrid systems, the optimization problem to solve at each sampling instant becomes a Mixed Integer Quadratic Programming (MIQP) problem. These problems have in general exponential computational complexity in the number of discrete variables and are known to be $\mathcal{NP}$-hard. In order to be able to solve such optimization problems in real time, it is necessary to decrease the computational effort needed. Research has been done on utilizing structure when solving these MIQP problems. The result are presented in the Licentiate thesis of Daniel Axehill, [7].

## 8.4 Multiuser Detection

When the optimal multiuser detection problem is formulated as a maximum likelihood problem, a binary quadratic programming problem has to be solved. A preprosessing algorithm has been developed which is able to compute almost all variables in the problem, even though the system is heavily loaded and affected by noise. The results have been presented in [66, 26].

## 8.5 Optimization algorithms for system analysis and identification

The Ph.D. thesis of Ragnar Wallin **??** deals with efficient algorithms for solving semidefinite programs originating from the Kalman-Yakubovich-Popov (KYP) lemma and algorithms for system identification when data samples are missing.

Many important examples of optimization in control and signal processing applications involve semidefinite programming with linear matrix inequality constraints derived from the KYP lemma. These include linear system design and analysis, robust control analysis using integral quadratic constraints, quadratic Lyapunov function search, and filter design. The structure of such a semidefinite program is

$$\begin{aligned} &\min\ \langle C, P\rangle + c^T x \\ &\text{s.t. } \mathcal{F}(P) + M_0 + \mathcal{G}(x) \geq 0 \end{aligned} \tag{8.1}$$

Where the inner product $\langle C, P\rangle$ is Trace$(CP)$,

$$\mathcal{F}(P) = \begin{bmatrix} A^T P + PA & PB \\ B^T P & 0 \end{bmatrix} \tag{8.2}$$

and

$$\mathcal{G}(x) = \sum_{k=1}^{p} x_k M_k \tag{8.3}$$

whith $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C, P \in \mathbb{S}^n$ and $M_k \in \mathbb{S}^{n+m}$, $k = 0, 1, \ldots, p$. In industrial applications these semidefinite programs have a huge number of variables making them intractable for general purpose solvers. The computational complexity is of order $n^6$ per iteration. Two customized algorithms for solving KYP-SDPs are presented in the thesis and are compared to a third one.

The first algorithm is based on solving an equivalent dual to (8.1). In this dual optimization problem the number of variables are reduced significantly by finding a basis for the dual variable that fulfills the dual constraints. This can be done in a computationally cheap way. A number of Lyapunov equations has to be solved. From the solution of the equivalent dual the variables $P$ and $x$ that are optimal solutions to (8.1) can be recovered. The computational complexity for solving the equivalent dual is of order $n^4$ or $n^3$ per iteration. The lower cost requires that some additional stucture is present in the $A$-matrix.

The second algorithm is a cutting plane algorithm derived making a generalized Benders decomposition of (8.1). The generalized Benders decomposition is a popular choice for optimization problems that are hard to solve, for example due to nonconvexity. The KYP-SDP is convex and is thus considered an easy problem to solve. However, it turns out that the computational complexity can be reduced significantly by applying this teqnique. Experiments indicate that the computational complexity for this algorithm may be of an order as low as $n^3$.

In addition to the two algorithms, some preprocessing, of the semidefinite program, that may improve numerical properties is presented. It is also shown how to use the algortithms for stability regions different from the left half-plane.

Missing data is a common problem in control and signal processing applications. If this problem is not addressed in a proper way this often results in parameter estimates with large bias. In the thesis the maximum likelihood criterion for ARX models subject to missing data is discussed. Two algorithms for identifying ARX models are presented and are compared to the expectation maximization algorithm. It is shown what property of the data it is that determines why one model is more likely to have produced the data than another and the problem with multiple optima is discussed.

# 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). He is an honorary member of the Hungarian Academy of Engineering, and a Foreign Associate of the US National Academy of Engineering (NAE). He is also an IEEE Fellow and an IFAC Advisor, and associate editor of several journals. He has received honorary doctor degrees from the Baltic State Technical University in S:t Petersburg, Russia (1996), from Uppsala University, Uppsala, Sweden (1998), from l'Université de Technologie de Troyes, France (2004) and from the Katholieke Universiteit in Leuven, Belgium (2004). In 2002 he received the Quazza medal from IFAC, and in 2003 the Hendryk W. Bode Lecture Prize from the IEEE Control Systems Society.

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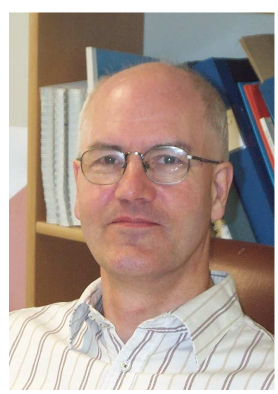

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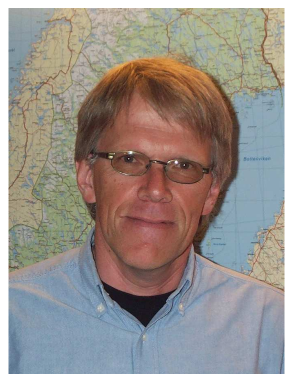

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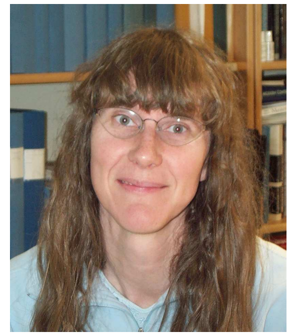

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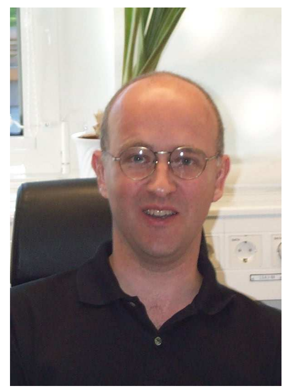

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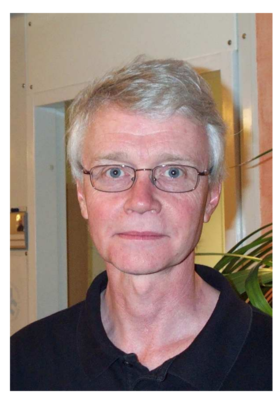

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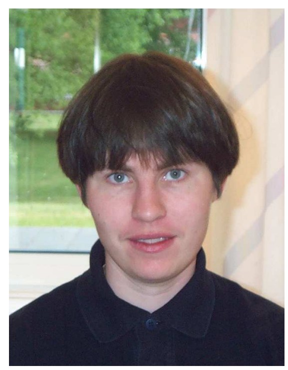

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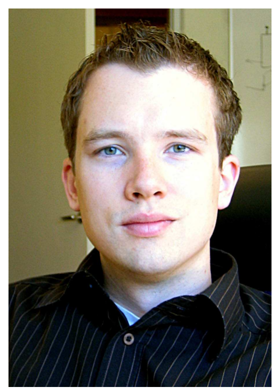

*Andreas Eidehall* was born in 1977. He received his M. Sc. in Applied Physics and Electrical Engineering in 2002 and his Lic. Eng. in 2004 both at Linköping University. He is employed by Volvo Car Corporation.

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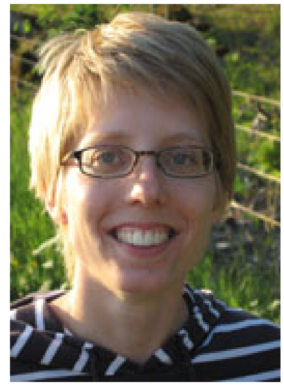


*Stig Moberg* was born in 1962. In 1986, he received his M. Sc. in Engineering Physics from Uppsala University. He is currently employed by ABB Robotics and his research interests are in the area of industrial robot control.

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*Ulla Salaneck* is the very valuable secretary for the control group.
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# 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 Mechanical Engineering. 152 participants. Lecturer: Inger Klein.

  Y Applied Physics and Electrical Engineering. 140 participants. Lecturer: Mikael Norrlöf

  D Computer Engineering. 110 participants. Lecturer: Anna Hagenblad.

  I Industrial Engineering and Management. 133 participants. Lecturer: Svante Gunnarsson.

  TB, KB Engineering Biology and Chemical Biology Programs. 102 participants. Lecturer: Torkel Glad.

- *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. 96 participants. Lecturer: Torkel Glad.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management and Mechanical Engineering Programs. Multivariable systems, Sampled data systems, LQG-control. 6 Participants. Lecturer: Torkel Glad.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Modelling, Bond graphs, System Identification, Nonlinear systems, Signal processing. 11 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. 98 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. 152 participants. Lecturer: Lennart Ljung and Jacob Roll.

- *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. 110 participants. Lecturer: Anders Hansson.

- *Real Time Process Control* (Realtidsprocesser och reglering). For the Information Technology Program. Real time systems. PID control. 24 participants. Lecturer: Inger Klein.

- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, controllability, observability, feedback control. 24 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, 48 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. 4 Participants. Lecturer: Svante Gunnarsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Available for several Engineering Programs. 720 Participants. Lecturer: Anna Hagenblad and Jacob Roll.

- *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, 24 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, 22 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, 18 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, 55 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 and Ragnar Wallin.

## 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.

- *Optimal Control.* Lecturer Torkel Glad. Literature: Bryson A.E. and Ho Y.C.: Applied Optimal Control, Ginn and Company 1969.

# Appendix C

# Seminars

- *Control and Estimation of Automotive Powertrains with Backlash.* **Adam Lagerberg,** Högskolan i Jönköping, February 3, 2005.

- *Bayesian Treatment of Complex Covariance Matrices.* **Lennart Svensson,** Chalmers University of Technology. February 17, 2005.

- *Experiment design in system identification.* **Henrik Jansson,** Royal Institute of Technology, February 24, 2005.

- *Identification of linear systems with nonlinear distortions.* **Johan Schoukens,** Vrije Universiteit Brussel, March 1, 2005.

- *Identification of Continuous-Time Noise Models.* **Rik Pintelon,** Vrije Universiteit Brussel, March 3, 2005.

- *Periodic Signal Modeling Using Orbits of Nonlinear ODEs.* **Emad Abd-Elrady,** Uppsala University, March 10, 2005.

- *Beyond the Kalman Filter: Particle Filters for Tracking Applications.* **Neil Gordon,** DSTO, Australia, March 17, 2005.

- *The modified Riccati equation and its role in tracking, communications and control.* **Yvo Boers,** THALES, The Netherlands, March 17, 2005.

- *Topics in networked control.* **Karl Henrik Johansson,** Royal Institute of Technology, March 31, 2005.

- *Laplace Transforms - too difficult to teach, learn and apply, or just a matter of how to do it?* **Anna-Karin Carstensen,** Högskolan i Jönköping, April 7, 2005.

- *Projection Techniques for Identification.* **David Lindgren,** FOI, Linköping, April 14, 2005.

- *Robust control of a flexible robot arm: A benchmark problem.* **Stig Moberg,** ABB/LiU, April 21, 2005.

- *Applications of Process Control in Oil Refining.* **Nicholas Alsop,** Preemraff Lysekil, May 10, 2005.

- *Analysis by Optimization.* **Henrik Jonson,** SAAB Dynamics, May 19, 2005.

- *Control and Real-Time Computing Research in Lund.* **Karl-Erik Årzén,** Lund University., May 26, 2005.

- *Fuzzy Gain-Scheduled Visual Servoing for an Unmanned Helicopter.* **Bourhane Kadmiry,** Department of Computer and Information Science, Linköpings universitet, September 22, 2005.

- *Optimalare Styrning / "More Optimal" Control.* **Per Rutquist,** Volvo Technology Corporation / Chalmers, Göteborg, October 6, 2005.

- *Harmonic balance for uncertain systems.* **Ulf Jönsson,** Optimization and Systems Theory, Royal Institute of Technology, Stockholm, October 10, 2005.

- *Probing Control: Analysis and Design with Application to Fed-Batch Bioreactors.* **Stéphane Velut,** Lund University, October 27, 2005.

- *Identification of linear and bilinear systems with errors-in-variables.* **Mats Ekman,** Uppsala University, November 3, 2005.

- *Uppfinner du åt andra?* **Arne Jacobsson,** Universitetsholding, Linköpings universitet, November 17, 2005.

- *RRM and CRRM: an overview of IST-EVEREST activities.* **Oriol Sallent,** UPC-TSC, Barcelona, Spain, November 24, 2005.

# Appendix D

# Travels and Conferences

**Daniel Ankelhed** participated at the SIAM Conference on Optimization, Stockholm, May,2005.

**Daniel Axehill** participated at the The Eighth SIAM Conference on Optimization, Stockholm, May 2005, RadioVetenskap och Kommunikation 2005, Linköping, June 2005.

**Andreas Eidehall** participated in the conferences Safe Highways of the Future 2005 in Stuttgart, Germany, May 30, the IEEE Intelligent Vehicles 2005 in Las Vegas, USA, June 7 and the IEEE Intelligent Transportation Systems 2005 in Vienna, Austria, September 14.

**Martin Enqvist** participated in the 16th IFAC World Congress, Prague, Czech Republic, July, 2005, the 14th ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September, 2005, the International Symposium on Nonlinear Theory and Its Applications (NOLTA), Bruges, Belgium, October, 2005 and the 44th IEEE Conference on Decision and Control and the European Control Conference, Seville, Spain, December, 2005. Furthermore, he visited Vrije Universiteit Brussel in Belgium on October 21, 2005.

**Markus Gerdin** participated at the 14th ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September, 2005 and the 44th IEEE Conference on Decision and Control and European Control Conference ECC 2005, Seville, Spain, December, 2005.

**Christina Grönwall** participated in the SSBA symposium on Image Analysis, Malmö, Sweden, March 2005 and the IEEE Workshop on Advanced 3D Imaging for Safety and Security, San Diego, USA, 2005.

**Fredrik Gunnarsson** participated in the 61st Vehicular Technology Conference, Stockholm, Sweden, May 2005, the RadioVetenskap och Kommunikation Conference, Linköping, Sweden, June 2005, the 11th Swedish Workshop on Wireless Systems, Lilla Edet, Sweden, December 2005 and visited ITN, Norrköping, February and Chalmers, Gothenburg, September 2005 as Licentiate Thesis opponent.

**Svante Gunnarsson** participated in CDIO Collaborators meeting, Pretoria South Africa, February 2005, CDIO International Conference, Kingston Canada, June 2005, 16th IFAC World Congress, Prague Czech Republic, July 2005, 33rd SEFI Conference, Ankara Turkey, September 2005, CDIO Collaborators meeting, Liverpool UK, November 2005.

**Fredrik Gustafsson** attended the IEEE Statistical Signal Processing Workshop held in Bordeaux, August 22-24, and gave a plenary lecture "Challenges in Statistical Signal Processing for Automotive Safety Systems". He was a keynote speaker at SWAR (Swedish Workshop on Autonomous Robots) held in Stockholm, September 1, with the contribution "Autonomous GIS-supported positioning and navigation". He attended the 16th IFAC World Congress, Prague, Czech Republic, July 3-8, where he gave the presentation "System identification using Measurements Subject to Stochastic Time Jitter" and visited DTU, Denmark, October 6, and HUT, Helsinki, Finland, 18 November as PhD opponent.

**Anders Hansson** participated at IEEE Conference on Decision and Control, Sevilla, Spain, 2005.

**Janne Harju** participated at the SIAM Conference on Optimization, Stockholm, May, 2005.

**Kent Hartman** visited Lärarförbundet, Linköping Mars 1, Skolverket, Stockholm Mars 9, April 20 and Aug 31, participated at "Tekitdagen", Linköping, April 21, "Samverkan mellan skola och universitet", Linköping Oct 18.

**Gustaf Hendeby** visited the 16th IFAC World Congress, Prague, Czech Republic, July 2005 and the 44th IEEE Conference on Decision and

Control, and European Control Conference, Seville, Spain, December 2005.

**Jeroen Hol** participated at the project meeting (EU project, MATRIS) in London, United Kingdom,October 18-19.

**Rickard Karlsson** visited Thales, Henglo, The Netherlands, May 4, 2005, participated in 13th European Signal Processing Conference, EUSIPCO, Antalya , Turkey, 2005. 23/2: Brussels, Planning meeting for EU 7th frame program

**Lennart Ljung** participated in Meetings of the committee for the Dr. A. De Leeuw-Damry-Bourlart - Applied Sciences Prize, March 17 and May 12 in Brussels. May 18 –22 he took part in Symposium on Optimization and Control to honor Boris Polyak, Institute for Control Science, Moscow, June 8 – 13 in the First Annual Kailath Lectures and Colloquium, Stanford University, Stanforn CA. He participated in the 14th IFAC Congress, Prague, Czech Republic during July 3 – 8, and September 19-22 in the annual meeting of the European Reseacrh Network on System Identiffication, ERNSI, Louvain-La-Neuve, Belgium. He spent September 23 – October 15 as Russell Severence Springer Distinguished Professor in Mechanical Engineering and MacKay Professor in Electrical Engineering and Computer Sciences, UC Berkeley, CA, and took part in the International School "Nonlinear modelling of complex dynamical systems" ,University of Siena, Italy, November 16 – 18. Finally he participated in the European Control Conference and the IEEE Conference on Decision and Control, Seville, Spain, December 12 –15.

**Mikael Norrlöf** Participated at the 16th IFAC World Congress, Prague, Czech Republic, July 2005.

**Jacob Roll** participated at the HYCON WP3 meeting, Dortmund, Germany, April 20, BioMedSim, Vårdnäs, Sweden, May 2005, Quantitative Biology Workshop, Gothenburg, Sweden, June 2005, 16th IFAC World Congress, Prague, Czech Republic, July 2005, ERNSI Workshop (and a visit to SISTA, Katholieke Universiteit Leuven), Louvain-la-Neuve, Belgium, September 2005, and 44th IEEE Conference on Decision and Control and European Control Conference ECC 2005, Seville, Spain, December 2005.

**Ulla Salaneck** participated in the ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September 19-21 and in the "Rikssekreterarmötet" in Wien September 24-27 2005.

**Thomas Schön** visited the Institute of Statistical Mathematics, Tokyo, Japan on February 18. During the period February - May he visited the School of Electrical Engineering and Computer Science, University of Newcastle in Newcastle, Australia. He participated at the 16th IFAC World Congress, Prague, Czech Republic, July 3-8. September 19-21 he participated at ERNSI Workshop System Identification, Louvain-la-Neuve, Belgium. He also participated at the project meeting (EU project, MATRIS) in London, United Kingdom, October 18-19.

**David Törnqvist** participated at the 16th IFAC World Congress, Prague, Czech Republic, July, 2005.

**Erik Wernholt** participated at the 16th IFAC World Congress, Prague, July 3-8; and the 14th ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September 19-21.

# Appendix E

# Lectures by the Staff

- Daniel Axehill: *A Preprocessing Algorithm Applicable to the Multiuser Detection Problem- Poster presentation*, RadioVetenskap och Kommunikation 2005, Linköping, Sweden, June 14 – 16, 2005.

- Andreas Eidehall: *Emergency Lane Assist* Safe Highways of the Future 2005, Stuttgart, Germany, May 30, 2005.

- Andreas Eidehall: *The marginalized particle filter for automotive tracking applications* IEEE Intelligent Vehicles 2005, Las Vegas, USA, June 7, 2005.

- Andreas Eidehall: *A new approach to lane guidance systems* IEEE Intelligent Transportation Systems 2005, Vienna, Austria, September 14, 2005.

- Martin Enqvist: *Controllers for Amplitude Limited Model Error Models*, 16th IFAC World Congress, Prague, Czech Republic, July 4, 2005.

- Martin Enqvist: *Identification of Hammerstein Systems Using Separable Random Multisines*, 14th ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September 19, 2005.

- Martin Enqvist: *Benefits of the Input Minimum Phase Property for Linearization of Nonlinear Systems*, International Symposium on Nonlinear Theory and Its Applications (NOLTA), Bruges, Belgium, October 20, 2005.

- Martin Enqvist: *Linear Models of Nonlinear Systems*, Division of Vehicular Systems, Linköpings universitet, Linköping, Sweden, December 21, 2005.

- Markus Gerdin: *Well-Posedness of Filtering Problems for Stochastic Linear DAE Models*, 44th IEEE Conference on Decision and Control and European Control Conference ECC 2005, Seville, Spain, December 12, 2005.

- Jonas Gillberg: *Frequency Domain Identification of Continuous-time ARMA models from Sampled Data*, 16th IFAC World Congress, Prague Czech Republic, July 4, 2005.

- Jonas Gillberg: *requency Domain Identification of Continuous-time Outout-error models from Sampled Data*, 16th IFAC World Congress, Prague Czech Republic, July 4, 2005.

- Fredrik Gunnarsson: *System Aspects of WCDMA Uplink Parallel Interference Cancellation* 61st Vehicular Technology Conference, Stockholm, Sweden, May 31, 2005.

- Fredrik Gunnarsson: *Mobile Positioning Using Wireless Networks*, plenary talk, RadioVetenskap och Kommunikation Conference, Linköping, Sweden, June 15, 2005.

- Svante Gunnarsson: *Using an alumni survey as a tool for program evaluation*, CDIO International Conference, Kingston Canada, June 8, 2005.

- Svante Gunnarsson: *On identification of a flexible mechanical system using decimated data*, 16th IFAC World Congress, Prague Czech Republic, July 4, 2005.

- Svante Gunnarsson: *The CDIO Initiative from an automatic control project course perspective*, 16th IFAC World Congress, Prague Czech Republic, July 7, 2005.

- Svante Gunnarsson: *Redesign of the applied physics and electrical engineering (Y) program at Linköping Univesity accoding to CDIO* 33rd SEFI Conference, Ankara Turkey, September 8, 2005.

- Fredrik Gustafsson *Challenges in Statistical Signal Processing for Automotive Safety Systems* the IEEE Statistical Signal Processing Workshopheld, Bordeaux, August 22-24.

- Fredrik Gustafsson *Autonomous GIS-supported positioning and navigation*, SWAR (Swedish Workshop on Autonomous Robots), Stockholm, September 1.

- Gustaf Hendeby: *Fundamental Fault Detection Limitations in Linear Non-Gaussian Systems*, 44th IEEE Conference on Decision and Control, and European Control Conference, Seville, Spain, December 12, 2005.

- Rickard Karlsson: *Particle Filtering for Positioning and Tracking Applications*, Thales, Henglo, The Netherlands, May 4, 2005.

- Rickard Karlsson: *Particle Filtering for Positioning and Tracking Applications*, Saab Systems, Järfälla, Sweden, May 12, 2005.

- Rickard Karlsson: *Particle Filtering for Positioning and Tracking Applications*, FOI, Linköping, Sweden, May 24, 2005.

- Rickard Karlsson: *Particle Filtering for Positioning and Tracking Applications*, Saab Bofors Dynamics, Linköping, Sweden, May 25, 2005.

- Rickard Karlsson: *Particle Filtering for Quantized Sensor Information*, 13th European Signal Processing Conference, EUSIPCO, Antalya, Turkey, 2005.

- Lennart Ljung: *Controllers for amplitude limited model error models*, Symposium on Optimization and Control to honor Boris Polyak, Institute for Control Science, Moscow, May 19, 2005.

- Lennart Ljung: *Identification of Non-linear Dynamical Systems*, Department Colloquium Mechanical Engineering and Electrical Engineering, University of California at Berkeley, Berkeley, CA, October 8, 2005.

- Lennart Ljung: *Identification of Linear and Nonlinear Systems*, Series of 5 seminars, Department of Mechanical Engineering, University of California at Berkeley , Berkeley, CA, October 2005.

- Lennart Ljung: *Identification of Non-linear Dynamical Systems*, International School "Nonlinear modelling of complex dynamical systems", University of Siena, Italy, November 17, 2005.

- Lennart Ljung: *Identification for a purpose - Michel Gevers' impact on System Identification*, ERNSI Meeting, Louvain-La-Nueve, Belgium, September 21, 2005.

- Lennart Ljung: *Models and Modeling in Industry - Are we responding to the challenges*, Decmeber 14, ECC/CDC, Seville Spain, December 14, 2005.

- Stig Moberg: *Seminar: Swedish Open Championships in Robot Control*, ABB Robotics, Västerås, Sweden, February 21, 2005.

- Stig Moberg: *Control of Industrial Robots*, Department of Electrical Engineering, The Royal Inst of Technology, Stockholm, Sweden, May 20, 2005.

- Stig Moberg: *Control of Industrial Robots*, Dept of Machine Design, Mechatronics , The Royal Inst of Technology, Stockholm, Sweden, June 15, 2005.

- Stig Moberg: *Plenary Talk: Computational Intelligence for High-Precision Industrial Robots*, 6th IEEE International Symposium on Computational Intelligence in Robotics and Automation, Espoo, Finland, June 28, 2005.

- Stig Moberg: *Robust Control of a Flexible Manipulator Arm: A Benchmark Problem*, 16th IFAC World Congress, Prague, Czech Republic, July 4, 2005.

- Mikael Norrlöf: *Position Estimation and Modeling of a Flexible Industrial Robot*, 16th IFAC World Congress, Prague, Czech Republic, July 5, 2005.

- Mikael Norrlöf: *The industrial robot - past, present and future - from an automatic control perspective*, Docent lecture, Linköping University, August 29, 2005.

- Jacob Roll: *A General Direct Weight Optimization Framework for Nonlinear System Identification*, 16th IFAC World Congress, Prague, Czech Republic, July 4, 2005.

- Jacob Roll: *Consistent Nonparametric Estimation of NARX Systems Using Convex Optimization*, ERNSI Workshop, Louvain-la-Neuve, Belgium, September 19, 2005.

- Jacob Roll: *Control Theory and System Identification in Systems Biology: A few examples*, Seminar at Div. of Automatic Control, Linköping University, October 13, 2005.

- Jacob Roll: *Consistent Nonparametric Estimation of NARX Systems Using Convex Optimization*, 44th IEEE Conference on Decision and Control and European Control Conference ECC 2005, Seville, Spain, December 2005.

- Thomas Schön: *Nonlinear Estimation and Selected Applications*, The Institute of Statistical Mathematics, Tokyo, Japan, February 18, 2005.

- Thomas Schön: *Some Applications of System Estimation and Associated Theory*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, March 16, 2005 .

- Thomas Schön: *A Short Course on Particle Filters - Part I*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, March 22, 2005.

- Thomas Schön: *A Short Course on Particle Filters - Part II*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, March 23, 2005.

- Thomas Schön: *Integrated navigation of cameras for augmented reality*, 16th IFAC World Congress, Prague, Czech Republic, July 7, 2005.

- Thomas Schön: *Nonlinear System Identification Using the Expectation-Maximization Algorithm*, ERNSI, Louvain-la-Neuve, Belgium, September 21, 2005.

- David Törnqvist: *GLR Tests for Fault Detection over Sliding Data Windows*, 16th IFAC World Congress, Prague, Czech Republic, July 6, 2005.

- Erik Wernholt: *Nonlinear Grey-Box Identification of Industrial Robots Containing Flexibilities*, 16th IFAC World Congress, Prague, July 3-8, 2005.

- Erik Wernholt: *Nonlinear Grey-Box Identification of Industrial Robots Containing Flexibilities*, The 14th ERNSI Workshop on System Identification, Louvain-la-Neuve, Belgium, September 19-21, 2005.

# Appendix F

# Publications

## Phd Theses

[1] M. Enqvist. *Linear Models of Nonlinear Systems.* PhD thesis, Dec 2005.

[2] J. Jansson. *Collision Avoidance Theory with Application to Automotive Collision Mitigation.* PhD thesis, Linköping University, Linköping University, 581 83 Linköping, Sweden, June 2005.

[3] R. Karlsson. *Particle Filtering for Positioning and Tracking Applications.* PhD thesis, Mar 2005.

[4] D. Lindgren. *Projection Techniques for Classification and Identification.* PhD thesis, Jan 2005.

[5] E. G. Lundin. *Uplink Load in CDMA Cellular Radio Systems.* PhD thesis, Nov 2005.

[6] R. Wallin. *Optimization algorithms for system analysis and identification.* PhD thesis, Jan 2005.

## Licentiate Theses

[7] D. Axehill. Applications of integer quadratic programming in control and communication. Technical Report Licentiate Thesis no. 1218, De-

partment of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2005.

[8] G. Hendeby. Fundamental estimation and detection limits in linear non-Gaussian systems. Technical Report Licentiate Thesis no. 1199, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Nov. 2005.

# Journal Papers and Book Chapters

[9] A. Eidehall. Lane game. *Traffic Technology International Annual Review*, 1, Dec 2005.

[10] J. Elbornsson, F. Gustafsson, and J.-E. Eklund. Analysis of mismatch noise in randomly interleaved adc system. *IEEE Transactions on Circuit and Systems – I: Regular papers*, 52:465–476, March 2005. LiTH-ISY-R-2487.

[11] M. Enqvist and L. Ljung. Linear approximations of nonlinear fir systems for separable input processes. *Automatica*, 41(3):459–473, Mar 2005.

[12] C. Grönwall, F. Gustafsson, and M. Millnert. Ground target recognition using rectangle estimation. *IEEE Transactions on Image Processing*, (Submitted), Mar 2005.

[13] F. Gustafsson and F. Gunnarsson. Possibilities and fundamental limitations of positioning using wireless communication networks measurements. *IEEE Signal Processing Magazine, vol. 22, 4(41-53), 2005.*, 22, 4(41-53), Augu 2005.

[14] F. Gustafsson and F. Gunnarsson. Possibilities and fundamental limitations of positioning using wireless communication networks measurements. *Signal Processing Magazine*, 22(4), Jul 2005.

[15] O. Härkegård and T. Glad. Resolving actuator redundancy - optimal control vs. control allocation. *Automatica*, 41(1):137–144, Jan 2005.

[16] R. Karlsson and F. Gustafsson. Recursive bayesian estimation–bearings-only applications. *IEE Proceedings Radar, Sonar and Navigation*, 152(5):305–313, Oct 2005.

[17] R. Karlsson, T. Schön, and F. Gustafsson. Complexity analysis of the marginalized particle filter. *IEEE Transactions on Signal Processing*, 53(11):4408–4411, Nov 2005.

[18] S. L. Kukreja. A suboptimal bootstrap method for structure detection of non-linear output-error models with application to human ankle dynamics. *International Journal of Control*, 78(12):937–948, Aug 2005.

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