LINKÖPING UNIVERSITY
DIVISIONS OF AUTOMATIC CONTROL AND COMMUNICATION SYSTEMS
ACTIVITY REPORT
2001

Contents

Chapter 1

Introduction

The Divisions of Automatic Control and Communication Systems consist of some forty 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.

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 lasts for three more years.

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, Ola Härkegård, Jonas Roll and Ingela Lind defended their Lic. Eng. degree.

In November 2001, Anders Hansson joined the group as Lecturer in Automatic Control.

In the following pages the main research results obtained during 2001 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. The next chapeter 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 conferenec papers refer to a related department report that can be downloaded in .ps or .pdf format.

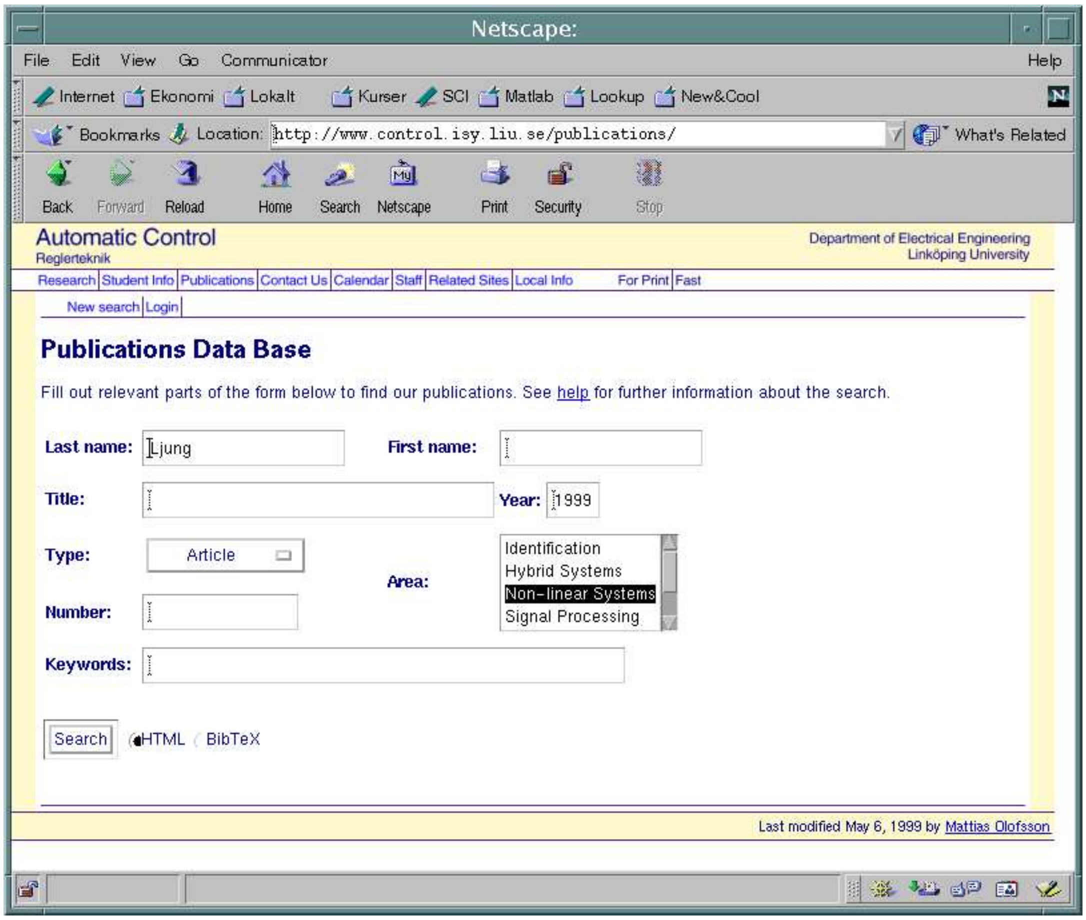

Figure 2.1: The publications data base interface

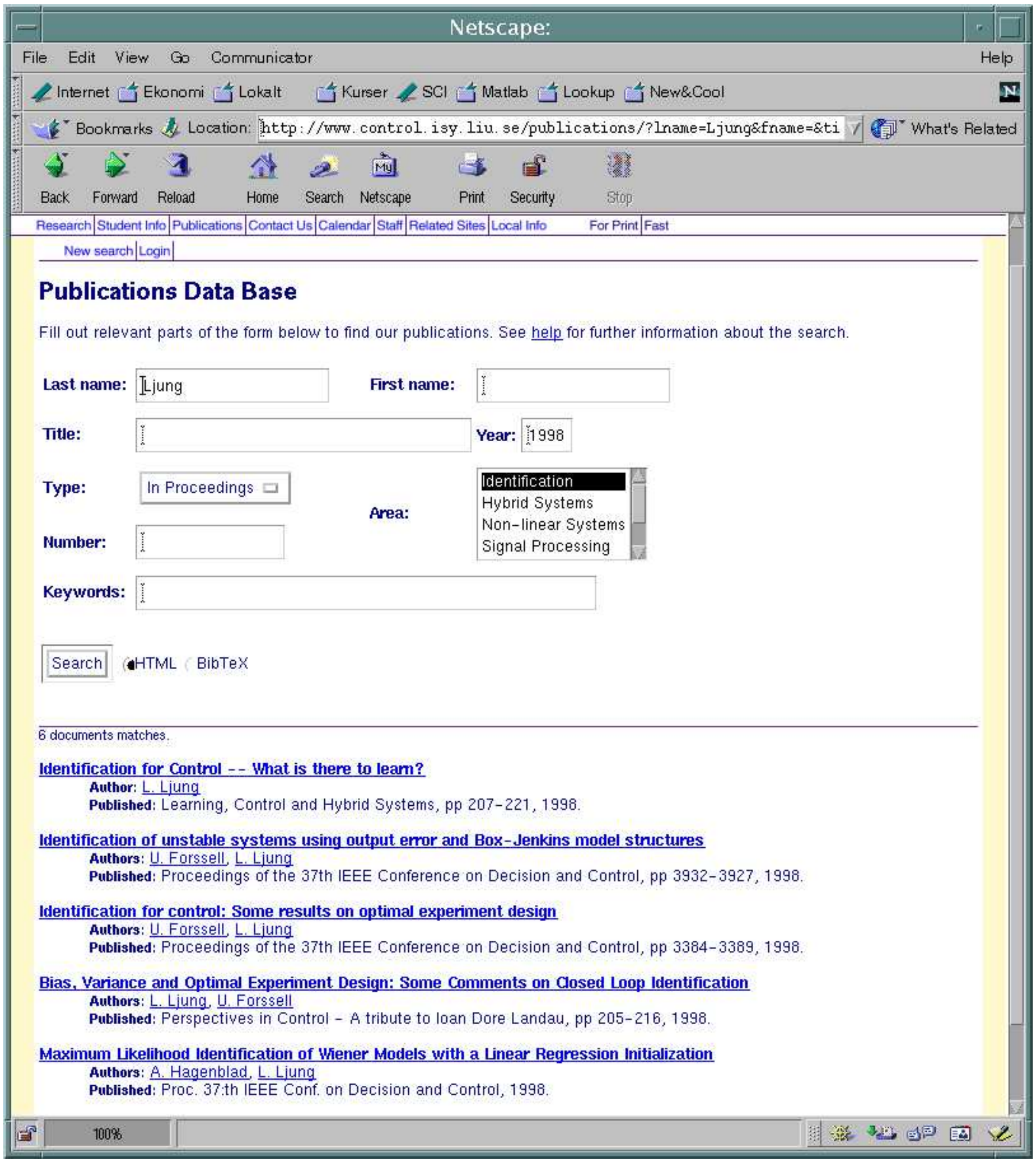

Figure 2.2: Example of search result

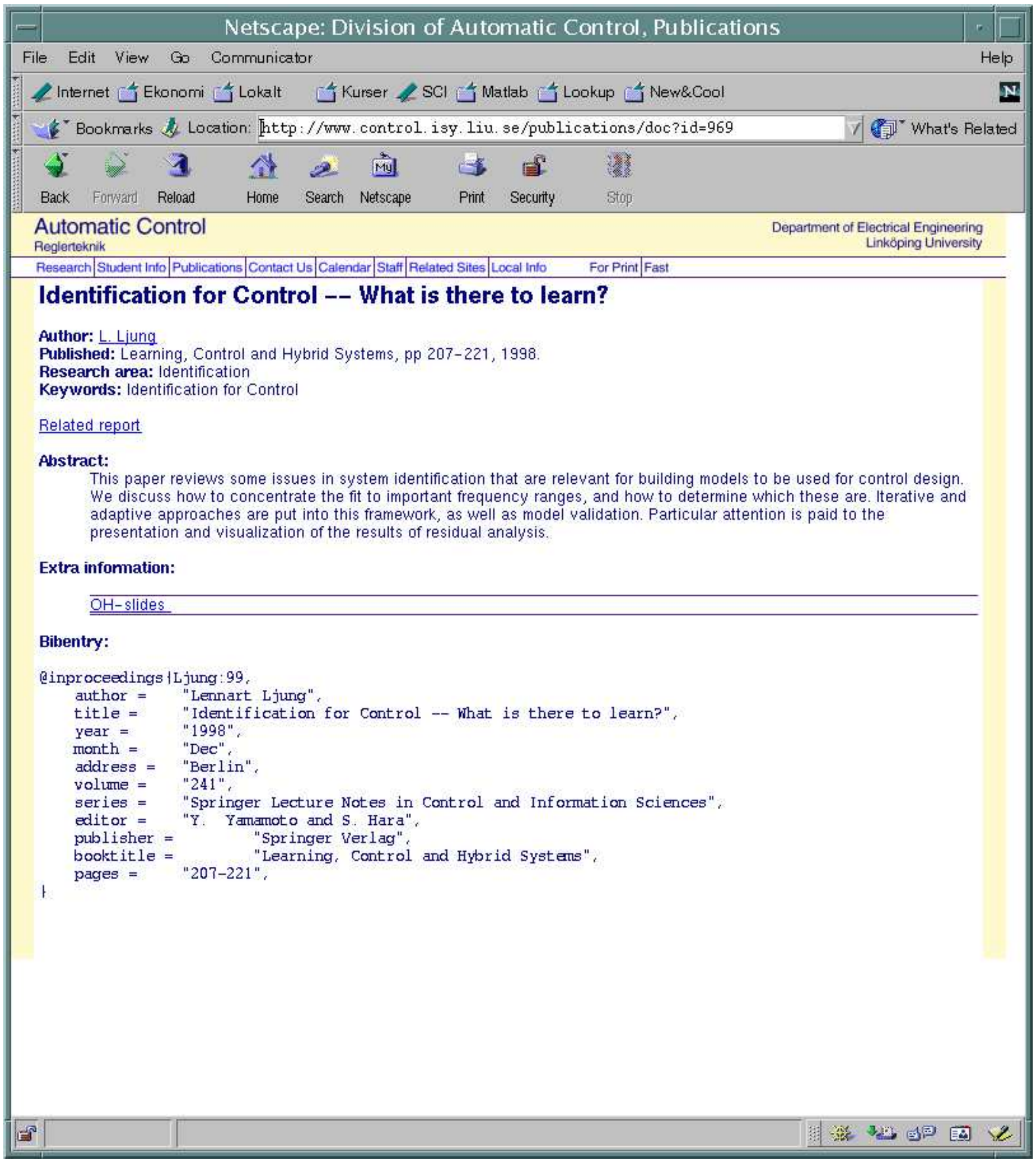

Figure 2.3: Example of a publication home page

Chapter 3

System Identification

3.1 Introduction

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

During 2001 two licentiate theses, [5], and [4] were defended. These will be described in the next two sections.

3.2 Determining model structures with ANOVA

Problem statement

Assume that a non-linear FIR model describes the measurements y_t from a system with input u_t, that is,

$$y_t = g(u_t, u_{t-T}, u_{t-2T}, ..., u_{t-kT}) + e_t.$$

The value of k is unknown in addition to which time lags of u_t that contributes to the value of y_t and g is an unknown static non-linear function of up to $k+1$ variables. If proper regressors could be found without too much effort, the problem of selecting the function g and estimate its parameters would be much easier.

The ANOVA Idea

The statistical analysis method ANOVA is a widely spread tool for finding out which factors contribute to given measurements. It has been used and discussed since the 1940's and is a common tool in medicine and quality control applications. ANOVA has been applied to the problem above in an approach, novel to the system identification area [5]. The main advantage of the method is that *no assumptions on the function g are needed.*

The method is based on hypothesis tests with F-distributed test variables computed from the residual quadratic sum, where the residuals are the difference between the measured output and the output from a very coarse model based on sample means. Depending on what hypotheses are tested to be true or false a corresponding model structure can be obtained. This model structure defines the selected regressors and what relation they should have in the model, that is, if they affect the output additively or with interaction. Various aspects and properties of ANOVA in system identification applications have been discussed in the Licentiate thesis [5].

Simulation Results

Results from several studies are lumped together in Table 3.1. The first study, columns one to four, compares exhaustive search with ANOVA, with different noise levels and different levels of significance for ANOVA. The second study investigates what happens when a random input signal is used (column five). The third study is made to see if extra caution is necessary when a correlated input signal is used (column six). For details, see [5].

The exhaustive search method is used to provide some comparison numbers, to get some perspective on how good or bad ANOVA is. An appropriate choice of $g(\cdot)$ is needed for this method. The idea behind the exhaustive search method to find the model structure is to enumerate all possible combinations of the regressors and estimate a model for each such combination. When all the models are estimated, their prediction performance are compared with some good measure, e.g., the root mean square(RMS) error between measured and predicted output. The one model that has the best performance is chosen as the model for the system.

Analysis method		Exh. search	ANOVA	Exh. search	ANOVA	ANOVA	ANOVA
No. of MC runs		100	100	100	100	50	50
Significance level		-	0.01	-	0.0001	0.01	0.01
Input signal		PRMS	PRMS	PRMS	PRMS	random	correlated
No. of input/output data		256	256	256	256	800	128-384
Noise standard deviation		1	1	0.0001	0.0001	0.0001	0.0001
No.	Function	col. 1	col. 2	col. 3	col. 4	col. 5	col. 6
1	$u_t - 0.03u_{t-2}$	10	5	94	100	52	14
2	$\ln\lvert u_t\rvert + u_{t-1} + e^{u_{t-2}}$	77	98	78	98	92	98
3	$u_{t-1} \cdot [u_t + \frac{1}{u_{t-2}}]$	100	98	100	100	100	100
4	$\operatorname{sgn}(u_{t-1})$	84	94	80	100	74	94
5	$\operatorname{sgn}(u_{t-1}) \cdot u_{t-2}$	93	96	92	100	90	100
6	$\operatorname{sgn}(u_{t-1}) \cdot u_t \cdot u_{t-2}$	100	100	100	100	100	100
7	$\ln\lvert u_{t-1} + u_{t-2}\rvert$	95	96	94	100	92	86
8	$\ln\lvert u_{t-1} \cdot u_{t-2}\rvert$	94	90	82	100	90	84
9	$u_{t-2} \cdot \ln\lvert u_{t-1}\rvert$	97	97	95	100	90	82
10	$u_{t-2}^3 \cdot \ln\lvert u_{t-1}\rvert$	50	95	56	100	90	90
11	$u_{t-2} \cdot (\ln\lvert u_{t-1}\rvert)^3$	93	95	91	99	90	98
12	$\lvert u_{t-2}\rvert \cdot e^{u_{t-1}}$	54	96	54	100	90	84
13	$u_{t-2} \cdot e^{u_{t-1}}$	49	94	49	100	88	94
14	$u_{t-2} \cdot e^{u_{t-1} - 0.03u_t}$	58	100	58	100	6	6
15	$\lvert u_t\rvert$	83	96	73	100	96	98
16	network						
	$g(u_{t-1}, u_{t-2})$	73	88	94	100	-	-

Table 3.1: Results from Monte-Carlo simulations. The first rows state the experiment setup and the last rows give the percentage of correctly chosen regressors. The input signals are a pseudo-random multi-level signal(PRMS), a random signal from a uniform distribution and a signal with strong correlation between adjacent time lags. For details see [5]

Conclusions

The main conclusions from the studies are:

- The method is reliable: ANOVA seldom fails to give correct results, and when it does, warning signals are given as failing assumption checks.
- The computations are fast and straightforward, without iterations or minimizations.
- ANOVA is easy to interpret.
- ANOVA is useful for varying kinds of input signals.
- ANOVA puts demands on the information contents in the input/output data, which will make further identification easier.
- ANOVA is not critically sensitive to the amount of measurement noise.

3.3 Verification and Identification of Piece-wiseAffine Systems

Robust Verification

Piecewise affine systems constitute an important subclass of hybrid systems, and consist of several affine dynamic subsystems, between which switchings occur at different occasions. As for hybrid systems in general, there has been a growing interest for piecewise affine systems in recent years, and they occur in many application areas.

In many cases, safety is an important issue, and there is a need for tools that prove that certain states are never reached, or that some states are reached in finite time. The process of proving these kinds of statements is called *verification*. Many verification tools for hybrid systems have emerged in the last ten years. They all depend on a model of the system, which will in practice be an approximation of the real system. Therefore it would be desirable to learn how large the model errors can be, before the verification is not valid anymore. In [4], a verification method for piecewise affine systems is presented, where bounds on the allowed model errors are given along with the verification. It is also suggested how this method can be combined with certain aspects of control design.

Identification of Piecewise Affine Systems

Piecewise affine systems occur naturally in many applications, but they can also be used as approximations of more general nonlinear systems. Hence, identification of piecewise affine systems is an important area. In [39] and [4], a new identification method based on mixed-integer programming is proposed. One notable property of the method is that the global optimum is guaranteed to be found within a finite number of steps. The complexity of the mixed-integer programming approach is discussed, and the special case of identification of Wiener models is considered in detail, since that model structure makes it possible to reduce the computational complexity (this is also considered in [33]). In [4], an overview of different approaches appearing in the literature is also presented, and some relations between the mixed-integer programming approach and existing approaches are pointed out. Furthermore, a combination of the mixed-integer programming approach and a local minimization approach is investigated.

3.4 Closed-loop Identification

The problem of identifying systems operating under output feedback, i.e., in closed-loop, is one that has gained a lot of interest in the identification literature during the years. The problem is of clear industrial importance since it is often the case that the plant under study is currently controlled by a regulator (that should be re-tuned) that cannot be disconnected during the experiment. The reason might be that the plant is open-loop unstable or that the identifier is not allowed to break the control loop for practical and/or economic reasons. Also, from a user's perspective it is important to know if it is possible to identify such systems and then how to this should be performed.

It turns out that most of the standard open-loop methods fail when applied directly to closed-loop data. The main reason for this is the inevitable correlation between the input and the additive output noise which models all disturbances in the system. Instrumental variables, correlation and spectral analysis and the subspace methods are examples of methods with problems in this situation. Luckily there are other methods that work and an important exception is the prediction error method. This method will work fine and give consistent estimates of the open loop system also with closed-loop data, given that the true system, including the noise properties, can be correctly modeled within the model class.

In 2001 we have studied some new expressions for accuracy analysis of the identified model. This has resulted in the article, [12]

3.5 Models on Demand

In this project, we focus on the identification of nonlinear models, and, in particular, on the situation that occurs when a very large amount of data is available.

Traditional treatments of the estimation problem in statistics and system identification have mainly focused on global modeling approaches, i.e., the model has been optimized on basis of the entire data set. However, when the number of observations grows very large, this approach becomes less attractive to deal with because of the difficulties in specifying model structure and the complexity of the associated optimization problem. Inspired by ideas from local modeling and database systems technology, we have taken a conceptually different point of view. We assume that all available data are stored in a database, and that models are built "on demand" as the actual need arises. When doing so, the bias/variance trade-off inherent to all modeling is optimized locally by adapting the number of data and their relative weighting. For this concept, the name *model-on-demand* has been adopted.

In [6] it is shown that the model-on-demand concept provides a very good way of estimating frequency functions of linear systems, using automatic, adaptive and frequency-dependent choices of frequency resolution. This gives several advantages over traditional spectral analysis techniques. The paper [19] the general procedure for the concept ios outlines.

3.6 Model Approximation, Model Error Modeling and Control Design

Much of recent research is dedicated to understand the two main uncertainty sources, leading to model errors: unmodeled dynamics and noise affecting the data. In [79], we discuss and compare three approaches to System Identification, that explicitly aim at separating these contributions: Goodwin's

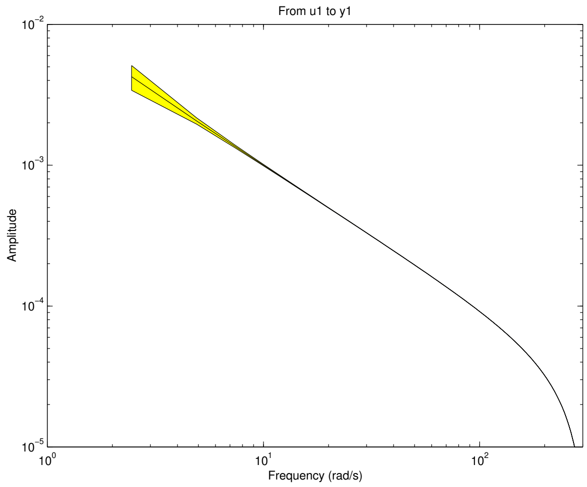

Figure 3.1: Amplitude Bode plot of the obtained model, with confidence regions corresponding to 3 standard deviations marked. Experiment B.

Stochastic Embedding, Model Error Modeling as described above (employing prediction error methods) and Set Membership Identification. An example, using (simulated) data from a non-linear plant, illustrates the methods.

A general problem formulation for understanding how general – non-linear, time-varying – systems are approximated by the conventional linear system identification paradigm is given in [10]. It also contains illustrations of how the gain of a model error model can be estimated ("estimating the distance between the true system and the linear approximation"). Figure 3.1 shows the amplitude Bode plot of an estimated linear model of a nonlinear system. The uncertainty region based on the conventional covariance estimate is also shown. This region is grossly underestimated. Figure 3.2 shows the corresponding estimate of an equivalent linear uncertainty region, based on a gain estimate of the model error model.

In [51] the model error concepts and model error modeling for control design are discussed in a broader perspective, focusing on stability robustness issues. Of special interest is how to make use of power based gain calculations, and how to deal with non-linear error models.

To complete the picture, [40] presents a framework for identification oriented robust controller design. Assuming an uncertain plant, directly identified from data by one of the methods described in [79], the set of all robustly

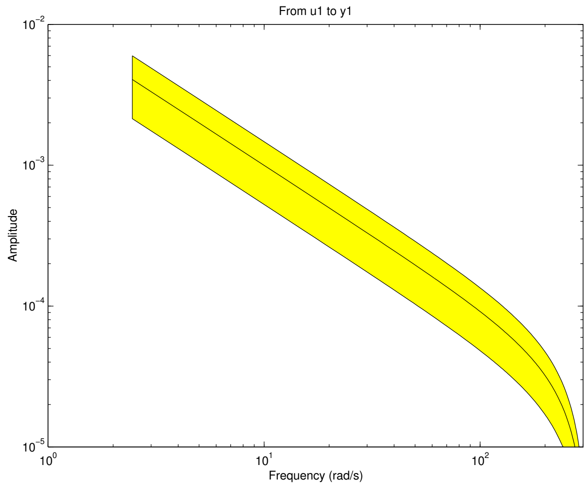

Figure 3.2: The resulting uncertainty model for Experiment A in Example 1. Left: Relative model error (i.e $W_1 = G_{nom}$) with $W_2 = H_{nom}$. Right: Relative model error with $W_2 = 1$.

stabilizing controllers, that additionally guarantee robust performance, is characterized by a system of second order cones, which can be efficiently solved using interior point algorithms.

3.7 Other Aspects on Identification Methods

Model Reduction

One way of estimating models from data is to first estimate a high order model which is then subjected to model reduction. In this way it is possible to keep track of the bias errors that are (possibly) present in the low order model. Another important aspect is the variance of the reduced model. This leads us to the question: Will it ever be better to estimate a low order model via model reduction than estimating the low order model directly from data? This is the topic that is discussed in Fredrik Tjärnström's lic thesis from 2000.. The somewhat surprising result is that using L_2 model reduction it could in some cases be strictly better to estimate the low order model using reduction techniques, and in most cases we get the same variance as the direct estimation would have given.

In [44, 97] the tools developed in this thesis are used to analyze variance properties of a two-step ARX estimation procedure. The main results from this analysis are a covariance expression for the final low order model that is easy to compute and an analysis on how to optimize this approach with respect to variance.

Mixed Estimation

Nowadays, there exists several well developed system identification methods. Typically these are based on different assumptions on the measurement noise acting on the system. In [117] a way to merge information from a set membership identification (SMI) and prediction error methods (PEM) to create an improved estimate compared to SMI and PEM is given. The approach is rather complex to analyze analytically, but simulations show very good results at a low computational cost on a number of different problems.

Asymptotic Covariance Estimates

There has been a considerable interest in useful asymptotic expressions for the covariance of the frequency function estimate. The basic expression is that

$$\mathrm{Cov}\hat{G}_N(e^{i\omega}) \sim \frac{n}{N}\frac{\Phi_v(\omega)}{\Phi_u(\omega)} \tag{3.1}$$

where n is the model order, N is the number of data and Φ_u and Φ_v are the input and noise spectra, respectively. It has been pointed out that, while this is surprisingly accurate in many cases, it could also be misleading for small n in other cases. In [17] we give expressions of this kind, that are not asymptotic in n. Moreover, we show that the convergence rate (in n) towards the asymptotic expression (3.1) is $1/n$, and display the mechanisms that make the exact expression differ from its limit.

Neural Networks

Some results for general structure observers of non-linear systems, based on continuous time state-space neural networks are derived and illustrated in [52] and [14].

Accelerated Convergence in Stochastic Approximation

It is well known that the simple LMS (gradient) method for estimating the parameters of a linear regression could be quite slow:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + \gamma(t)(y(t) - \varphi^T(t)\hat{\theta}(t-1)) \tag{3.2}$$

It has been known for a while that the asymptotic properties of this estimate can be improved towards the theoretic Cramer-Rao limit by a second round of averaging of $\hat{\theta}(t)$. In [13] we study this result from a different perspective, and display some underlying mechanisms, that also allow insight into the behavior when the gain does not tend to zero. The bottom line is that this accelerated convergence procedure behaves like the recursive least squares.

Optimal 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 that 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. Some partial results along these lines are given in a paper by D. Bauer and Ljung to appear in Automatica, May 2002.

Chapter 4

Nonlinear Systems

4.1 Constraints and Structures in Dynamic Systems

Extension of RGA to nonlinear systems

The relative gain array (RGA) has been widely used as a measure of the interaction between control loops in multivariable systems. For a linear system with square transfer matrix $G(s)$, the relative gain array is defined as

$$G_{RGA} = G. * G^{-T}$$

where ".*" denotes element-wise multiplication of the matrices, and $-T$ denotes the transpose of the inverse. The element i, j in the RGA array can be interpreted as the gain from input u_j to output y_i when the other u_k are zero ("all other loops open"), divided by the corresponding gain when all other y_k are zero ("all other loops have maximally tight control").

For a static nonlinear system

$$y = H(u)$$

it is proposed to define the RGA at a point u^0, y^0 as the following array of scalar functions

$$H_{ij}^{RGA} = \phi_{ij}(\psi_{ji}(y_i))$$

where

$$\begin{aligned}\phi_{ij}(u_j) &= H_i(u_1^0, \dots, u_{j-1}^0, u_j, u_{j+1}^0, \dots, u_m^0) \\ \psi_{ji}(y_i) &= \left(H^{-1}\right)_j (y_1^0, \dots, y_{i-1}^0, y_i, y_{i+1}^0, \dots, y_m^0)\end{aligned}$$

This definition can then be extended to dynamic systems by regarding H instead as an operator between function spaces. The practical computation can be done in a differential algebraic framework, [53].

Response time limitations

One effect of control constraints is that the response time of a system can not be arbitrarily fast. For a linear system the response time is described by the rise time or settling time of a step response. A more precise measure is the minimum time required for transfer from the origin to the new equilibrium defined by the step. In [9] a lower bound for the minimum time can be derived. Consider a linear system $G(s)$ whose input is constrained by

$$|u(t)| \leq u_0$$

A lower bound for the response time t_f of an output step of magnitude y_0 is

$$t_f \geq -\tau \log \left(1 - \frac{y_0}{G(0)u_0}\right)$$

where τ is the largest time constant of the system.

Algebraic Methods in Control

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

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

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

The problem of *Quantifier Elimination*, (QE) consists of finding a formula without quantified variables (without u in the above case) which is equivalent to the original formula. This is always possible according to a result in the late forties by A. Tarski. However, the calculations involved in this original algorithm was to complex to be of any practical value. Lately there has been an increasing interest in QE due to the rapid development of computer algebra.

The most efficient implementations of QE-algorithms today are based on *Cylindrical Algebraic Decompositions*, (CAD). The method constructs a decomposition of R^n such that a given set of polynomials have constant sign on each component. Such a decomposition is a starting point for the elimination of quantified variables from a formula.

In [53] many of the aspects concerning the use of quantifier elimination and other algebraic methods in control are described.

4.2 Backstepping in nonlinear and adaptive flight control

Aircraft flight control design is traditionally based on linear control theory, due to the existing wealth of tools for linear design and analysis. However, in order to achieve tactical advantages, modern fighter aircraft strive towards performing maneuvers outside the region where the dynamics of flight are linear, and the need for nonlinear tools arises.

In this research project we investigate backstepping as a new framework for nonlinear flight control design. Backstepping is a recently developed design tool for constructing globally stabilizing control laws for a certain class of nonlinear dynamic systems.

A discussion on the pros and cons of using backstepping compared to more conventional methods like gain-scheduling and feedback linearization, or nonlinear dynamic inversion, as it is usually referred to in the flight control society, can be found in [22].

In [46], backstepping is used to design a flight control system for angle of attack control, velocity-vector roll control, and sideslip regulation. The key idea of the backstepping design is to benefit from the naturally stabilizing aerodynamic forces acting on the aircraft. The resulting state feedback control laws thereby rely on less knowledge of these forces compared to control laws based on feedback linearization, which today is the prevailing nonlinear design technique within aircraft flight control. The backstepping control laws proposed are shown to be inverse optimal with respect to a meaningful cost functionals. This gives the control laws certain gain margins which implies that stability is preserved for a certain amount of control surface saturation.

In [54], the problem of handling a model error appearing at the input of a nonlinear dynamic system is treated, by considering the model error as an unknown, additive disturbance. Two schemes, based on adaptive backstepping and nonlinear observer design, are proposed for estimating and adapting to such a disturbance. These can be used to deal with model errors in the description of the aerodynamic moments acting on an aircraft.

In March 2001, a licentiate thesis [2] covering all these topics, and also including computed simulations using a realistic fighter aircraft model, was presented.

4.3 Model Predictive Control

In Model Predictive Control (MPC) an optimal control problem over a finite horizon is solved. A Licenciate thesis [1] containing various topics in MPC was defended during the year. The material in the thesis can be divided into two areas; approaches to guarantee stability in linear MPC, and robust formulations of MPC.

In most approaches to guarantee stability in linear MPC, there is a trade-off between guaranteed stability and feasibility. In the first part of the thesis, it was shown how previous results on synthesis of MPC with guaranteed stability could be extended to give less conservative results. Furthermore, it was shown how the feasibility issues could be analyzed.

The second part of the thesis was devoted to robust formulations of MPC. More precisely, it was shown that a minimax performance measures, assuming a system with "unknown-but-bounded" external disturbances, could be addressed using linear matrix inequalities and semidefinite programming. The results in the thesis have later been analyzed and extended in [88, 89].

The key ideas used for robust synthesis in the thesis have been used in the related work [90]. Instead of assuming external disturbances, it was assumed that the uncertainty in the system comes from an uncertain gain (the B matrix in a state-space representation). Once again, a minimax performance measure was used, and the problem was solved using semidefinite programming.

Another part of the research focused on synthesis of MPC controllers for nonlinear system. In [32], it was shown how tools from modern nonlinear control theory, such as back-stepping and Lyapunov synthesis, can be used in a completely nonlinear design of an MPC controller with guaranteed stability for unconstrained nonlinear systems.

4.4 Semi-Definite Programming for Integral Quadratic Constraints

In this project we investigate how to implement an efficient interior-point algorithm for the semi-definite programs that result from integral quadratic constraints. In [62, 64] the algorithm used is a primal-dual potential reduction method, where the computational effort is dominated by a least-squares system that has to be solved in each iteration. The key to an efficient implementation is to utilize iterative methods and the specific structure of integral quadratic constraints. The algorithm has been implemented in Matlab. To give a rough idea of the efficiencies obtained, it is possible to solve problems resulting in a linear matrix inequality of dimension 130×130 with approximately 5000 variables in about 5 minutes on a lap-top. Problems with approximately 20000 variable and a linear matrix inequality of dimension 230×230 are solved in about 45 minutes.

4.5 Switched Bond graphs

In the simulation of hybrid systems discontinuities can appear at mode changes. A switched bond graph approach to this problem is presented in [11]. An algorithm that gives initial values for the continuous state variables is derived from the switched bond graph representation of the system. It handles discontinuities introduced by a changed number of state variables at a mode change. The algorithm is obtained by integrating the bond graph relations over the mode change and assuming that the physical variables are bounded. This gives a relation between the variables before and after the mode change. It is proved that the equations for the new initial conditions are solvable.

The algorithm is related to singular perturbation theory by replacing the discontinuity by a fast continuous change. The action of a single switch tuned by a single parameter is considered. By letting this parameter tend to zero, the same initial state values are achieved as the ones derived by the presented algorithm. The algorithm is also related to physical principles like charge conservation.

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). A highlight of the year is the invited paper [71], which surveys six different applications involving collaboration with six different companies. An extended version will appear in IEEE Trans. on Signal Processing.

5.1 Terrain navigation

The research conducted in the area of sensor fusion has been focused on the application of terrain aided aircraft navigation. In this application an aircraft position is autonomously determined by fusing measurements from an inertial navigation system, a digital map and a radar altimeter. By measuring the terrain height variations along the aircraft flight-path and comparing these with a digital terrain map, a position estimate of the aircraft is obtained. The comparison between the map and the measurements is a nonlinear estimation problem where unconventional and conceptually different sources of information are fused together. Research as been focused on finding a reliable and effective algorithm for this position determination.

During this work, close contact has been established both with Saab Dynamics and Saab Military Aircraft. A full-scale commercial implementation of a company secret solution has been developed at Saab during a period of two decades. Their expertise in this application field has proved extremely useful when developing and testing new ideas.

An effective algorithm solving the terrain-aided navigation problem has been developed and implemented. Simulation tests comparing the newly developed method with the full-scale implementation at Saab shows outstanding performance of the new method, both concerning the speed of convergence of the algorithm and the steady state estimation accuracy. The superior performance is obtained at a fairly low computational cost which allows for online implementation.

Furthermore, the terrain-aided navigation problem has been analyzed and fundamental bounds on the achievable performance have been derived. The implemented method developed in this work has been shown to meet these bounds in extensive simulation evaluations. The bounds have also been used to derive information maps which can be used to support mission planning.

More recently, work has been directed towards the general issue of on-line estimation for non-linear and non-Gaussian state space models. The experience from the terrain navigation application have been generalized and applied to the recursive estimation problem. Work has been conducted in the area of simulation based methods for nonlinear estimation. This is a currently very hot area which promise tractable solutions to high dimensional estimation problems. Algorithms for simulation based estimation in recursive estimation have been studied, and applied to the terrain navigation application. General bounds for nonlinear recursive estimation have also been developed. The project is presented in detail in:

- N. Bergman, *Recursive Bayesian Estimation: Navigation and Tracking Applications*, 1999.
- N. Bergman, L. Ljung and F. Gustafsson *Terrain Navigation using Bayesian Statistics* IEEE Control Systems Magazine 19(3), June 1999.

A couple of master thesis 2000 describe real-time implementation of the algorithm in the Swedish fighter JAS 39 Gripen, where a prototype is currently running, and an alternative implementation using particle filters.

5.2 Particle filters for navigation and tracking

The recently published PhD thesis mentioned above summarizes the results of the sensor fusion project obtained hitherto. The current focus of the project is directed towards further penetrating the literature on the subject of simulation based estimation algorithms. Several Master thesis projects have been initated and are currently active in the area of sensor fusion. Two PhD students are working on particle filters within the ISIS Competence Center:

- Per-Johan Nordlund, Primary data and navigation group, Saab Gripen. In this project, the complexity of a particle filter applied to a navigation model, which has around 16 states, is addressed. The key contribution is to isolate the non-linear part, where a particle filter is really needed, and the (almost) linear part where the Kalman filter works well.

- Rickard Karlsson, Sensor fusion group, Saab Bofors Dynamics. The project aims at using particle filters for target tracking. Passive ranging and data association have been recent research topics.

Both Per-Johan and Rickard have several years of industrial experience and will continue to work one day per week at their respective industrial companies.

Particle filters for target tracking

Figure 5.1: Air to air passive ranging.

Many target tracking applications can be studied using a Bayesian formulation. Traditionally, linear or linearized models are used, where the uncertainty in the sensor and motion models is typically modeled by Gaussian densities. Hence, classical sub-optimal Bayesian methods based on linearized Kalman filters can be used. The sequential Monte Carlo method, or particle filter, provides an approximative solution to the non-linear and non-Gaussian estimation problem. The particle filter approximates the optimal solution, hence it can outperform the Kalman filter in many cases, given sufficient computational resources.

Let $x_t \in \mathbb{R}^n$ denote the state of the observed system and $\mathbb{Y}_t = \{y_i\}_{i=1}^t$ be the set of observations until present time. Consider the following non-linear discrete-time tracking system

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

with process noise v_t and measurement noise e_t. The process noise reflect the unknown target maneuver and the measurement noise the sensor errors. The non-linear prediction density $p(x_t|\mathbb{Y}_{t-1})$ and filtering density $p(x_t|\mathbb{Y}_t)$ for the Bayesian interference are given by

$$\begin{aligned} p(x_{t+1}|\mathbb{Y}_t) &= \int_{\mathbb{R}^n} p(x_{t+1}|x_t)p(x_t|\mathbb{Y}_t)dx_t \\ p(x_t|\mathbb{Y}_t) &= \frac{p(y_t|x_t)p(x_t|\mathbb{Y}_{t-1})}{p(y_t|\mathbb{Y}_{t-1})}. \end{aligned}$$

Sequential Monte Carlo methods, or particle filters, provide an approximative Bayesian solution to discrete-time recursive problem by updating an approximative description of the posterior filtering density.

The Monte Carlo filter approximates the probability density $p(x_t|\mathbb{Y}_t)$ by a large set of N particles $\{x_t^{(i)}\}_{i=1}^N$, where each particle has an assigned relative weight, $w_t^{(i)}$, such that all weights sum to unity. The location and weight of each particle reflect the value of the density in the region of the state space. The particle filter updates the particle location and the corresponding weights recursively with each new observation.

The posterior is estimated by a delta-Dirac sum using the importance weights

$$p(x_t|\mathbb{Y}_{t-1}) \approx \sum_{i=1}^{N} \tilde{w}_t^{(i)} \delta(x_t - x_t^{(i)}),$$

where $w_t^{(i)} \propto p(y_t|x_t^{(i)})$ and $\tilde{w}_t^{(i)}$ is the normalize weights. The recursive solution using particle filters may be implemented using the *sampling importance resampling* (SIR) algorithm from Gordon et. al. 1993.

In Figure 5.2 the particle filter method is demonstrated where the particles or samples are used to visualize the posterior.

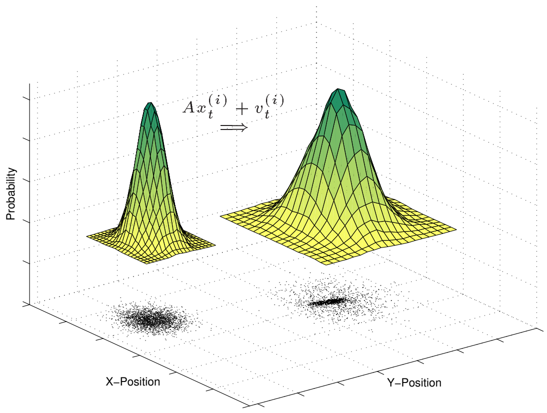

Figure 5.2: Probability density using the SIR method.

Angle-only tracking. In Figure 5.1 an air-to-air passive ranging is presented. The passive ranging or angle-only tracking application, when only angle information is available has been investigated. In [35] an air-to-air application is studied where the particle filter is compared to a banke of linearize Kalman filters. Also the choice of coordinate system is discussed, where Cartesian and modified spherical systems are used.

Monte Carlo data association. In [60] a multi-target data association application a simulation based approach for data association is proposed and compared to classical algorithms for an air-to-air tracking application. Moreover, the number of particles needed in the particle filter is adapted using a control structure to reduce the computational complexity.

Particle filters for integrated navigation

This project is currently focused on finding feasible estimation algorithms for integrated aircraft navigation. Integrated navigation means that measurements from two or more navigation sensors are fused to provide a more accurate and reliable navigation solution. The sensors we have been concentrating on are the inertial navigation system together with terrain-aided positioning. The challenge here consists of finding algorithms that solve the recursive Bayesian estimation problem for a system which is highly nonlinear (terrain-aided positioning) and at the same time is high-dimensional (inertial navigation).

This is an extension of the previous terrain-aided navigation project (see Section 5.1), which focused on horizontal position only. We know from this earlier project that recursive Monte Carlo methods, or particle filters, provide a promising solution to the two-dimensional terrain-aided positioning. However, increasing the dimension, including the entire spectra of states given by the inertial navigation system, makes the standard particle filter extremely ineffective. This calls for Rao-Blackwellization techniques, meaning that we marginalise the full conditional posterior density with respect to linear (or almost linear) parts, and estimate these parts using multiple Kalman filters. The remaining low-dimensional part of the state vector is estimated using the particle filter. For details on the Rao-Blackwellization method see [71, 23, 38].

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.

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. The post-processing amounts to finding a cause-effect relation between the generated error messages in a fault scenario, and then to choose the most significant error message(s) according to this relation, or to chose an unobservable critical event explaining the error messages.

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.

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

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.

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.

We advocate a two tier design with the structural model fault isolation as a first phase and a second phase of behavioral model fault isolation that 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. When starting behavioral model fault isolation we thus have a limited set of root candidates, i.e. events in the scenario that are suspected to have caused the failure of the system.

We use state charts in the UML class diagrams as notation for the behavioral model, and have developed a compiler, called SAD, that performs reasoning about a given scenario in terms of a behavioral model of the system, SD, and a log of events, OBS, together with a set of root candidates. SAD works in three phases in order to make the set of root candidates as small as possible. SAD uses SMV, a symbolic model-checker to reason about temporal order of events.

First, it is checked that SD and OBS are consistent. This does not make the set of root candidates smaller, but the phase is necessary for further reasoning. In SD we make a distinction between critical events that can cause system failure, and normal events that cannot. In the second phase, all events that cannot be root events are removed, i.e. we remove every event from the set of root candidates that needs some other critical event to be enabled. Finally SAD finds out whether any of the events remaining in the set necessarily has been present in the scenario, given SD and OBS. If that is the case, all non present events are removed.

Hopefully, we end up in a situation where the set of root candidates is a singleton set. This means that the event in question is either the only possible root, which is a very result strong, or else it is the only event that is known to be present in the scenario and also a possible root.

SAD is described in [20] and [68].

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 occured.

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.

6.3 Fault identifiability of additive faults in linear systems

In [48], we derive a Kalman filter based on data from a sliding window. This is used for *fault identification* in fault detection and diagnosis, where the additive fault is augmented to the state vector, and fault identification then becomes a Kalman filter problem. The algorithm is based on two Kalman filters: one state estimate from past data is compared to the state estimate of some of the future data. We suggest a method to judge the quality of diagnosis in a simple way. For fault estimation in the diagnosis, the general concept of *stochastic observability* in linear systems is introduced. Its role on the design step is illustrated on a problem of estimating the true velocity of a car, see Figure 6.1.

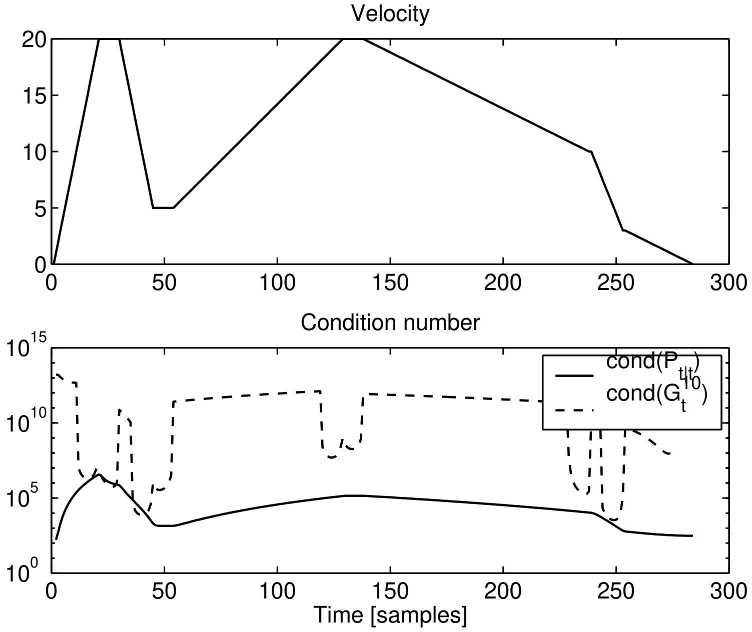

Figure 6.1: Simulated velocity profile (above), and two condition numbers (below). The first condition number (solid) is for the Kalman filter covariance matrix for the augmented fault state, which does not reveal the difficulty to estimate the fault state during segments of constant acceleration. The second condition number is for the fault observability matrix over a sliding window, and here it is apparent that the fault is only observable when the acceleration changes.

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.

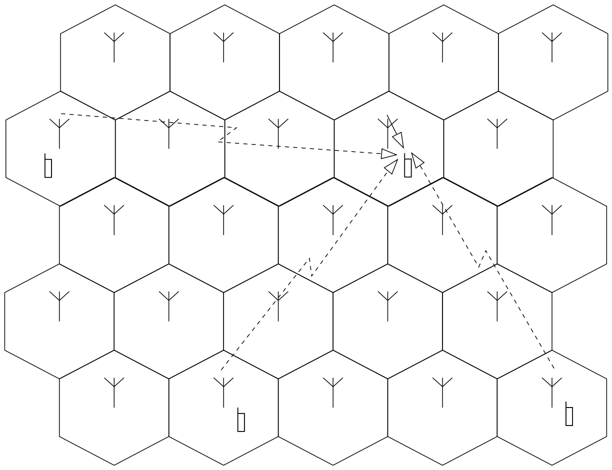

Figure 7.1: Downlink communications in a wireless network. The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

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 mechanisms 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 consists 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 keep the power consumption and price at low levels, CMOS

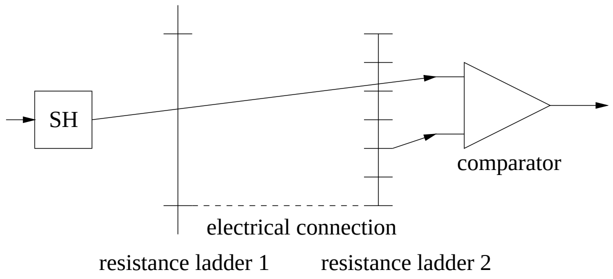

Figure 7.2: Two stage subranging SA-ADC. The conversion is done in two steps with two resistance ladders.

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. The algorithm is described in [3, 57]. The algorithm has also been evaluated on measurements from a three stage subranging A/D converter [58].

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.

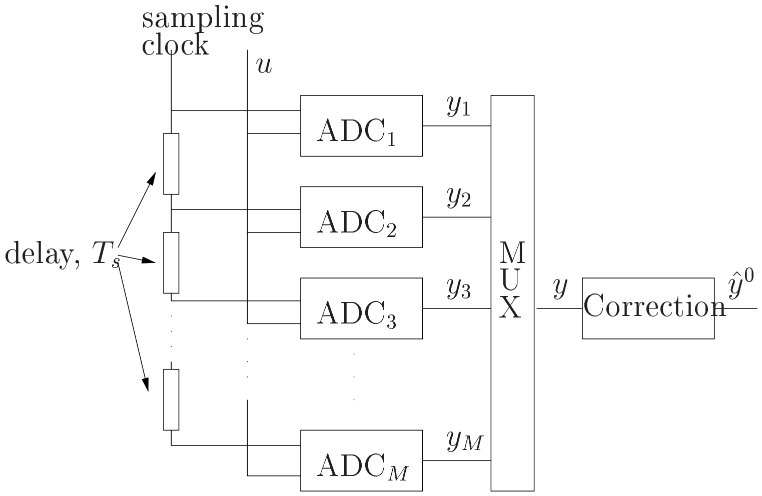

Figure 7.3: M parallel ADCs with the same master clock.

Due to this parallel, 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. The method is further described in [3, 112, 59]. The algorithm has also been evaluated on measurements from a dual A/D converter system [113].

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

Two important feedback situations are typically considered:

- **Information feedback.** The mobile feeds back the exact SIR measurements or the error

$$e(t) = \gamma^t - \gamma_{dB}(t). \tag{7.1}$$

  The important characterization is essentially that real numbers are fed back.

- **Decision feedback.** In a power control setting, we typically associate this with feedback of the sign of the error in (7.1)

$$s(t) = \text{sign}(\gamma^t - \gamma_{dB}(t)) = \text{sign}(e(t)) \tag{7.2}$$

  Thus, only one bit is needed for command signaling, which makes the scheme bandwidth efficient.

In practice, the assumption of real valued measurements of information feedback is unrealistic. Instead, quantized measurements can be made available.

Decision feedback is implemented in practice in the upcoming 3G systems, and the local loops can be considered as linear except for relay feedback. Therefore, the resulting oscillatory behavior can be analyzed using discrete-time describing functions [8]. Essentially, the performance is limited by the time delays in the local control loops. These time delays can be compensated for by using the Smith predictor to form Time Delay Compensation (TDC) [15].

Properties like stability and convergence are typical global properties related to the overall system. 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 [45].

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 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. See also [70].

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

$$L_j = 1 - \frac{N_j}{I_j^{tot}} \Longleftrightarrow I_j^{tot} = \frac{N_j}{1 - L_j} \tag{7.3}$$

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 recevied power. The proposed uplink relative load estimate [28, 27] is focused on WCDMA. It utilizes measurements readily available in that system, either periodically scheduled or from handover events. Initially, it is utilized in admission control, and it is easy to configure, and provides the possibility to predict the uplink load given that a specific user would be admitted in the system.

Furthermore, multi-services are naturally handled, and availability of high data-rate services are automatically limited with respect to coverage, compared to services of lower data-rate. This is illustrated by Figure 7.4, where the 192 kbps service is only available relatively close to the base stations (where users have higher power gains), while the speech service is available essentially everywhere.

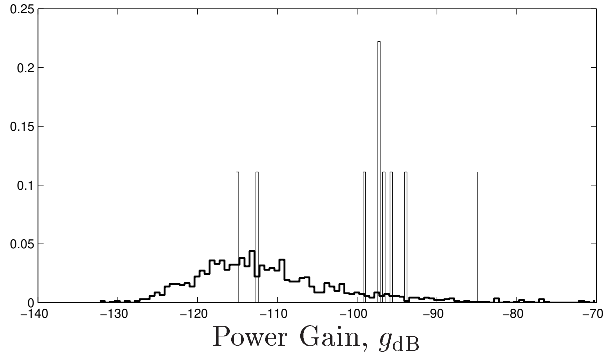

Figure 7.4: Histograms of power gains for admitted users with the services: 12.2 kbps (thick line) and 192 kbps (thin line).

Related results on capacity and relative load of cellular radio system, and with modeling of power control algorithms are further explored in [45].

Fredrik Gunnarsson, Fredrik Gustafsson and Erik Geijer Lundin are working in this project, which is an ISIS project in coopeation 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.

An investigation of the performance of TCP has been done in [30, 29], where the occupation of the queue is used as the primary performance measure. Here a simualtion model developed using simulink and stateflow is used, as well as the more complex network simulator developed at Berkeley, *ns-2*. A small *ns-2* simulation scenario is depicted in Figure 7.5.

Until now mainly heuristic methods have been used in the communication world to tune parameters and choose algorithms. There is a need for models that fit into existing frameworks such as control theory, probability theory and optimization theory.

Current work is developing a model of the network load when using TCP

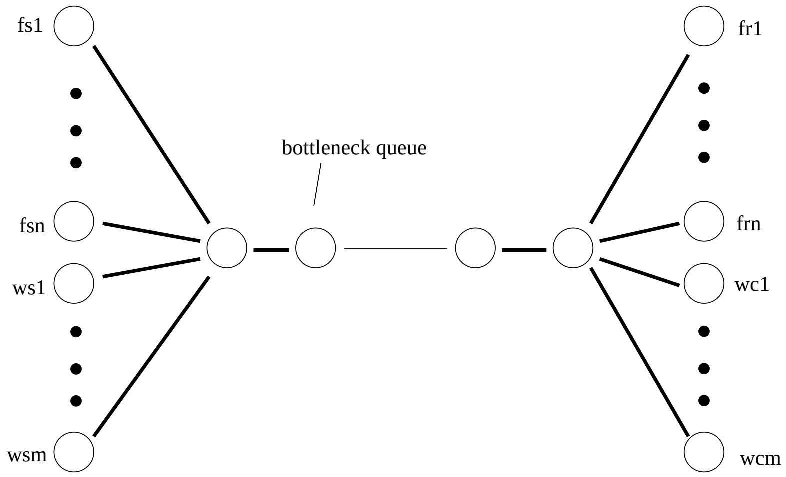

Figure 7.5: A *ns-2* simulation scenario with n file senders, fsi, with corresponding file receivers, fri, and m web servers, wsi, with corresponding web clients, wci.

traffic and use this to find a good controller of the load. The aim is to use known control theory concepts and techniques. An investigation is carried out concerning performance measures and adaptive queue management techniques for this purpose. 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 Automation Technology Products – 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 method that is applicable when the system is carrying out the same operation iteratively, and this is a common situation in many robot applications. The structure of the problem is shown in Figure 8.1, where the system G is controlled by a conventional control system including both feed-forward and feed-back, represented by the F_f and F respectively. The variables $d_k(t)$ and $n_k(t)$ denote load and measurement disturbances respectively. In addition to the control signals generated by these blocks a correction signal u_k is added. Alternatively the correction signal can be used as a feed-forward signal added to the control signal generated by the existing feed-back and feed-forward controllers. By evaluating the performance of the control system after one cycle it is possible to update the correction signal such that the error in the next cycle is reduced.

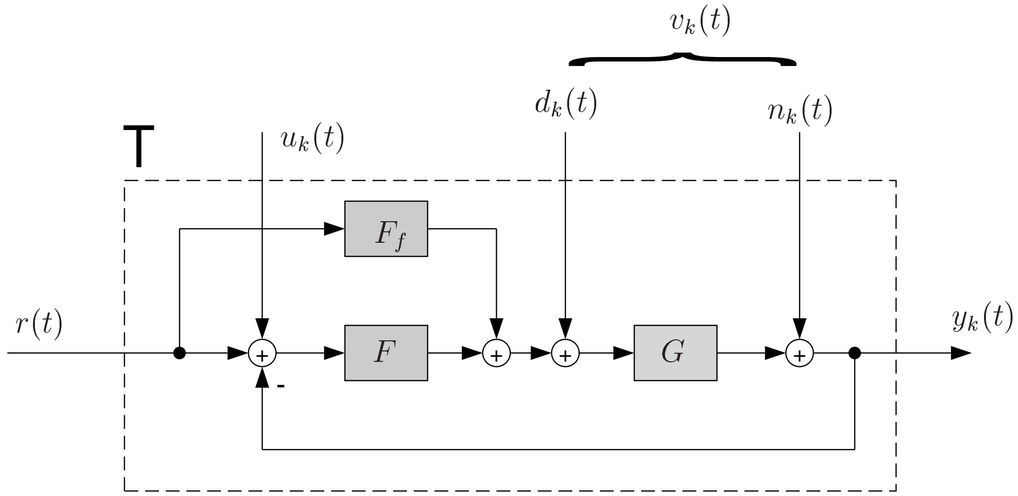

Figure 8.1: Control system.

One important aspect that has been covered during 2001 is the effect of disturbances on a system controlled with an ILC algorithm. A design method for systems with measurement disturbance and model uncertaintiy is presented in [37]. [37] covers design, analysis and experimental evaluation of a novel adaptive ILC algorithm. The algorithm is derived using a state space description of the problem. This enables the use of a Kalman state estimator for optimal handling of the disturbances.

Another contribution where the effect of measurement and load disturbances on ILC systems is studied is [7]. In this paper expressions for the disturbance effects are computed in the frequency domain. The theory is also illustrated by simulation examples and real experiments on the ABB IRB1400 robot installed in the lab at the Division of Automatic Control.

In [18] a systematic design method for the filters in an ILC algorithm is described. The design is based upon minimization of a quadratic criterion and a matrix representation of the system controlled by ILC. One of the results is that the algorithm in [18] can be used also for non-minimum phase systems, without giving an asymptotically unstable solution. Linear and non-linear non-minimum phase systems are also the main topics of [61]. The main idea is that the system controlled by ILC can be linearized, represented by a linear time invariant non-minimum phase system. Instead of just inverting this system and using it as the L filter in the ILC algorithm the idea is to factorize the linear system in a minimum phase part and a non-minimum-phase part,

$$G(z) = G_+(z)G_-(z)$$

The stable invers to $G_+(z)$ is causal while the stable inverse to $G_-(z)$ is anti-causal. The anti-causal filtering is realizable since the ILC algorithm is applied on a finite time interval and when computing u_{k+1} all of u_k and e_k in

$$u_{k+1}(t) = u_k(t) + L(q)e_k(t)$$

is available.

8.3 Robot Identification and Control

For design of algorithms for both control and diagnosis of industrial robots it is important to have good models describing the dynamical behavior of the robot. In [36] some work in this area is presented. Using data collected from the ABB IRB1400 operating in closed loop when the robot moves around axis one both black-box and physically parameterized models are identified with good results. The identification using physical parameters is based on the three-mass model shown in Figure 8.2 and the identified parameters are the moments of inertia, stiffness and damping of the springs and friction of the motor inertia. In [55] it is discussed how the regulator stability affects the achievable performance in control of flexible systems.

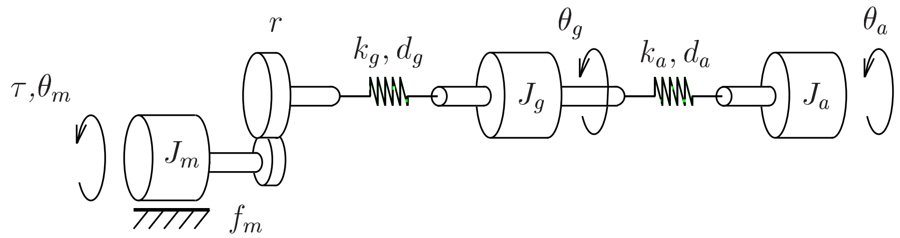

Figure 8.2: Three-mass flexible model.

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).
email: `ljung@isy.liu.se`

Torkel Glad was born in Lund, Sweden in 1947. He received his M.Sc. degree in engineering physics in 1970 and the Ph.D. degree in automatic control in 1976, both from the Lund Institute of Technology, Lund, Sweden. Since 1988 he is Professor of Nonlinear Control systems in the department. His research interests include Nonlinear Systems, algebraic aspects of System Theory and Optimal Control.
email: `torkel@isy.liu.se`

Mille Millnert is a Professor in the department. He was born in 1952 and received his M.Sc. in 1977 and his Ph.D. in Automatic Control 1982 from Linköping University. His research interests are Model Based Signal Processing, Parameter Estimation and the Combination of Numerical and Symbolical techniques in Signal Processing and Control. Since July 1996 he is Dean of the School of Engineering at Linköping University.
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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. Since 1989 he is associate professor at the department, and his research interests are system identification and adaptive control.
`email: svante@isy.liu.se`

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 asociate 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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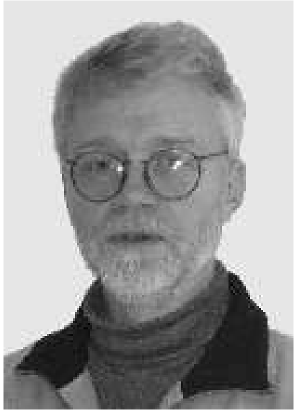
Anders Hansson Anders Hansson was born in Trelleborg, Sweden, in 1964. He received the M.Sc. 1989, Lic.Eng. in 1991, and the Ph.D. in 1995, all from Lund University, Lund, Sweden. From 1995 to 1998 he was employed by the Information Systems Lab, Stanford University. From 1998 to 2000 he was associate 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.

`email: hansson@isy.liu.se`

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.
email: hartman@isy.liu.se



Anders Helmersson was born in 1957. In 1981, he received his M. Sc. in Applied Physics at Lund Institute of Technology. He has been with Saab Ericsson Space since 1984. In 1993 he joined the Control Group where he received his Ph.D in 1995. His research interest is mainly in robust control and gain scheduling. He is currently employed by Saab AB and is an adjunct professor at the Division of Automatic Control.
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Anders Stenman was born in Gävle, Sweden in 1966. He received his M.Sc. in Computer Science and Engineering in 1993, his Lic.Eng. in Automatic Control in 1997 and his Ph.D. in 1999 all at Linköping University. He now works at NIRA Dynamics, Inc.
email: stenman@isy.liu.se

Anna Hagenblad was born in Lycksele, Sweden, in 1971. She received her M. Sc. degree in Applied Physics and Electrical Engineering in 1995 and her Lic. Eng. in 1999. Her research interests are in the area of identification, particularly of the nonlinear Wiener model.
`email: annah@isy.liu.se`

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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Fredrik Gunnarsson was born in 1971 He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 his Lic.Eng. in 1998 and his Ph.D in 2000, all at Linköping University. His current research interest is in the field of Radio Network Control. He also works part time at Ericsson AB.
`email:fred@isy.liu.se`

Fredrik Tjärnström was born in 1973. He received his M.Sc. Applied Physics and Electrical Engineering in 1997 and his Lic.Eng. in 2000 both at Linköping University. His research interests is uncertainty estimation of estimated models.
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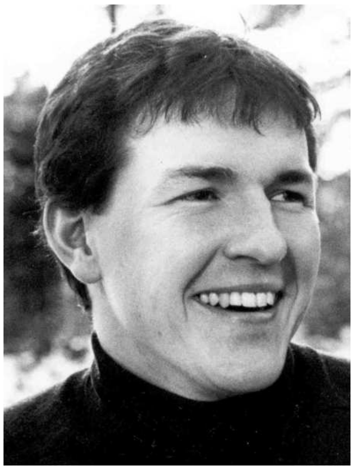

Ingela Lind was born in 1975. She received her M.Sc. in Applied Physics and Electrical Engineering in 1998 and her Lic.Eng. in 2001 both at Linköping University. Current research interest is regressor selection for online linear black-box models.
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Johan Löfberg was born in 1974. He received his M.Sc. in Mechanical Engineering in 1997 and his Lic.Eng. in 2001 both at Linköping University.
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Ola Härkegård was born in 1973. He received his M.Sc. Applied Physics and Electrical Engineering in 1998 and his Lic.Eng. in 2001 both at Linköping University.
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Måns Östring was born in 1974. He received his M.Sc. in Applied Physics and Electrical Engineering in 1998 at Linköping University. His current research area is robotic systems with focus on fault detection.
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Jonas Elbornsson was born in 1975. He received his M.Sc. in Applied Physics and Electrical Engineering in 1998 and his Lic.Eng. in 2001 both at Linköping University.
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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 both 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 at Linköping University. He is also employed by Saab Bofors Dynamics from where he is partly on leave to complete his Ph.D.
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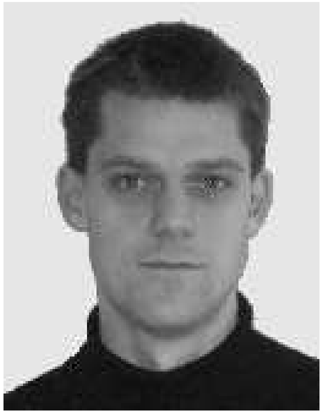

Per-Johan Nordlund was born in 1971. He received his M.Sc. in Applied Physics and Electrical Engineering in 1997 at Linköping University. He is also employed by Saab AB from where he is partly on leave to complete his Ph.D.
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Jonas Jansson was born in 1973. He received his M.Sc. in Applied Physics and Electrical Engineering in 1999 from Linköping University. He is also employed by Volvo AB from where he is partly on leave to complete his Ph.D.
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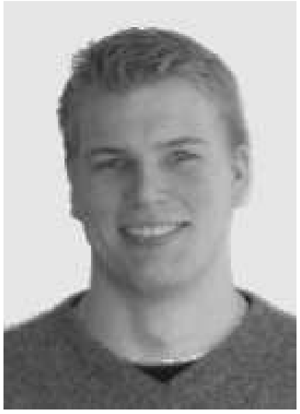

Frida Gunnarsson was born in 1977. She received her M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
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Martin Enqvist was born in 1976. He received his M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
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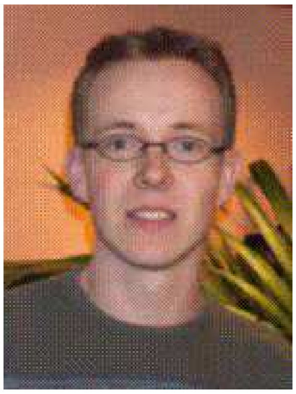

Svante Björklund was born in 1968. He received his M.Sc in Applied Physics and Electrical Engineering in 1993 from Linköping University.
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Christina Grönwall was born in 1968. She received her M.Sc. in Applied Physics and Electrical Engineering in 1992, from Luleå University of Technology and her Lic.Eng. in 2001 from Linköping University. She is employed by FOI from where she is partly on leave to complete her Ph.D.
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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 from the Royal Institute of Technology, Stockholm. His research interests include optimization for MPC.
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Jonas Gillberg was born in 1975. He received his M.Sc. in Applied Physics and Electrical Engineering in 2001 from Linköping University.
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Thomas Schön was born in 1977. He received his M.Sc. in Applied Physics and Electrical Engineering in 2001 from Linköping University.
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Wolfgang Reinelt Paderborn University, Paderborn, Germany was a post doctoral fellow from January 1999 to January 2001 and a guest researcher until September 2001.
email: `wolle@isy.liu.se`

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.
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Sören Hansson is engineer responsible for laboratory equipment.
email: `sorha@isy.liu.se`

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

Visitors

Vincent Verdult, University of Twente, Twente, The Netherlands, visited the department during March - May 2001.

Alxander Nazin, Institute of Control Sciences, RAS, Moscow, Russia, visited the department during April and June 2001.

Sunil Kukreja, McGill University, Montreal, Canada, is a postdoctoral fellow from September 2001.

Dalius Navakauskas, Vilnius Gidiminas Technical University, Vilnius, Lithuania, visited the department from October 2001 to March 2002.

Xavier Bombois, Delft University of Technology, Delft, The Netherlands, visited the department during October - November 2001.

Joe Qin, University of Texas at Austin, Austin, TX, visited the department during October 2001.

Appendix B

Courses

B.1 Undergraduate Courses

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

- *Automatic Control* (Reglerteknik) The basic control course given for all engineering programs. *Contents*: The feedback concept, PID-controllers, Frequency domain design techniques, Sensitivity and robustness, State space models and state feedback controllers, Observers.

M+TB Mechanical Engineering and Engineering Biology Programs. 190 participants. Lecturer: Anna Hagenblad.

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

D Computer Engineering Program. 120 participants. Lecturer: Anna Hagenblad.

I Industrial Engineering and Management. 150 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. 60 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. 15 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. 65 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. 25 participants. Lecturer: Inger Klein.

- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, controllability, observability, feedback control. 25 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, 20 Participants. Lecturer: Wolfgang Reinelt.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Avaliable for several Engineering Programs. 1000 Participants. Lecturer: Fredrik Gustafsson.

Anna Hagenblad and Inger Klein attended the 12th EAEEIE Annual Conference on Innovations in Education for Electrical and Information Engineering to present a paper about how to use problem based learning to teach control theory [31].

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

- *Automatic control, EI* (Electrical Engineering) 5 units, 40 participants. Contents: Dynamical systems, the feedback principle, frequency domain analysis and design of control systems, robustness and sensitivity of control systems, sampling, implementation, some examples of nonlinearities in control systems. Simulation of dynamic systems. Lecturer: Kent Hartman.

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

- *Automatic control, MI/KI* (Mechanical Engineering and Chemical Engineering) 4 units, 90 participants. Contents: Sequential control and logic controllers. Fundamentals of automatic control, dynamical systems, feedback, differential equations, frequency analysis, Bode plots, stability, simple controllers, sampling, implementation, simulation of dynamic systems. Lecturer: Kent Hartman.

B.2 Graduate Courses

- *Nonlinear systems.* Lecturer: Torkel Glad. Literature: T. Glad, Lecture notes on control of nonlinear systems.

- *Robust multivariable control.* Lecturer: Anders Helmersson. Literature: K. Zhou, J.C. Doyle and K. Glover: Robust and optimal control, Prentice Hall 1995.

- *Hybrid systems.* Lecturer: Inger Klein, Simin Nadjm-Tehrani (Department of Computer and Information Science), and participants of the course. Literature: Articles.

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 19 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
- 1 Sun SPARCserver 10 (2*2 hyperSPARC)
- 24 Sunblade 100
- 8 Sun Ultra 10
- 4 Sun Ultra 1
- 2 Dell OptiPlex PC:s
- 1 HP LaserJet 4 Si/MX Postscript laser printer

- 1 HP LaserJet 8100DN Postscript laser printer
- 1 HP ColorJet Postscript laser printer
- 1 HP LaserJet 5 MPPostscript laser printer
- 1 Tektronix Phaser 350 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
- 6 Dell Workstation 400
- 8 Network Crimson single Pentium III with dSPACE signal processing cards
- 3 Dell Workstation 340
- 2 Dell Workstation 220 with Allan Bradley SLC500 PLC system
- 1 LEO 386 computers with Metrabyte Dash 16 interfaces (A/D, D/A and digital I/O).
- 1 HP LaserJet 4 MP laser printer

Appendix D

Seminars

- *On Condition Monitoring of Control Loops.* **Alexander Horch**, Royal Institute of Technology, February 8, 2001
- *Active Safety Developments at Volvo Car.* **Jonas Johansson**, Volvo Car Corporation, February 15, 2001
- *Active Safety Developments at Volvo Car.* **Jonas Johansson**, Volvo Car Corporation, February 15, 2001
- *Identification of Multivariable Hammerstein Systems using Rational Orthonormal Bases.* **Juan Carlos Gomez**, Universidad Nacional de Rosario, Argentina, February 16, 2001
- *Periodic Modeling and Analysis of Power Systems.* **Erik Möllerstedt**, Lund University, February 22, 2001
- *The Saab NetDefence Concept.* **Anders Lundqvist**, Saab AB, March 7, 2001
- *Density and Flow: A Different View on Nonlinear Control.* **Anders Rantzer**, Lund University, March 22, 2001
- *Helikoptermodellering och helikopterstyrning inom WITAS.* **Erik Skarman**, Saab AB, March 29, 2001
- *2001-4-5 Identification for control in a prediction error framework: L2 and L-infinity methods.* **Håkan Hjalmarsson**, Royal Institute of Technology, April 5, 2001

- *Subspace Identification of Multivariable Linear Parameter-Varying Systems.* **Vincent Verdult**, University of Twente, April 19, 2001
- *Information Lower Bounds and Optimal Algorithms for Minimum Variance Adaptive Control Problems.* **Alexander V. Nazin**, Institute of Control Sciences, Moscow, April 20
- *Structure of the FFT and Peak-to-Average Power in OFDM Signals.* **James P. LeBlanc**, Luleå University of Technology, April 24, 2001
- *Sensorfusion för fordonsdynamikapplikationer.* **Urban Forssell**, NIRA Dynamics AB, April 26, 2001
- *Modelica and the ThermoFluid Model Library.* **Jonas Eborn**, Lund University. May 3, 2001
- *Antennas and Propagation from a Signal Processing Perspective.* **Thomas Svantesson**, Chalmers University of Technology, May 31, 2001
- *Assessing measurement for feedforward control.* **Mikael Petersson**, ABB, June 7, 2001
- *Engineering of Complex Adaptive Systems using OpEMCSS.* **John R. Clymer**, California State University Fullerton, June 8, 2001
- *Subspace Approaches to Dynamic Model Identification and Fault Diagnosis.* **Joe Qin**, University of Texas, October 16, 2001
- *Connecting Prediction Error Identification and Robust Control Analysis: a new framework.* **Xavier Bombois**, TU Delft, Delft, The Netherlands, October 18, 2001
- *An Overview of Industrial Model Predictive Control.* **Joe Qin**, University of Texas, October 25, 2001
- *Control Software, with emphasis on SLICOT software.* **Vasile Sima**, ICI Bucharest, October 30, 2001
- *Dynamic Artificial Neural Networks and Their Application in Speech Signal Processing.* **Dalius Navakauskas**, Vilnius Gedimines Technical University, Vilnius, Lithuania, November 1, 2001

Appendix E

Travel and Conferences

Jonas Elbornsson participated in the IEEE International Conference on Acoustics, Speech and Signal Processing, Salt Lake City, USA, May 7-11 2001 and in the European Solid State Circuits Conference, Villach, Austria, September 18-20 2001.

Martin Enqvist participated in the ERNSI Workshop on System Identification in Cambridge, UK, September 16-19.

Erik Geijer Lundin participated in International Conference on Communication, Helsinki, Finland, 11-14 June 2001 and in the Nordic Radio Symposium, Nynäshamn, Sweden, 3-5 April 2001.

Torkel Glad participated in the Russian - Swedish Control Conference, Moscow, Russia, May 14-16, in the NOLCOS, St Petersburg, Russia, July 4-6, and the IFAC Symposium on System Structure and Control in Prague, August 29-31.

Fredrik Gunnarsson participated in Nordic Radio Symposium, Nynäshamn, 3-5 April 2001, in International Conference in Communications, Helsinki, Finland, 10-14 June 2001, in Vehicular Technology Conference Fall, Atlantic City, NJ, USA, 7-11 October 2001 and in the Swedish Workshop on Wireless Systems, Åhus, 3-4 December 2001.

Frida Gunnarsson participated in the Nordic Radio Symposium, Nynäshamn, Sweden, 3-5 April 2001 and in IEEE International Conference on Communications, Helsinki, Finland, 11-14 June 2001.

Svante Gunnarsson participated in the 32nd International Symposium on Robotics, Seoul, Korea, 19-21 April, 2001.

Fredrik Gustafsson participated in the Society of Automotive Engineers World Congress, Detroit, March, 2001, the International Conference on Signal and Speech Processing (ICASSP), Salt Lake City, May, 2001, the 2001 Workshop on Hybrid methods for Control (H2C), Berlin, June, 2001, and the Statistical signal processing workshop, Singapore, August, 2001.

Anna Hagenblad participated in the EAEEIE 12th International Conference on Innovations in Education for Electrical and Information Engineering, Nancy, France, 14-16 May 2001, and in the ERNSI workshop, Cambridge, Great Britain, 17-19 September 2001.

Anders Hansson participated in the 2001 American Control Conference in Arlington, Virginia, June 25-27, where he co-organized a workshop on New Directions in Automatic Tuning and an invited session on Problem-specific Algorithms for Large-scale LMI Problems. He also participated in the Forth SIAM Conference on Linear Algebra in Signals, Systems, and Control in Boston, Massachusetts, August 13-15. On January 26 he was opponent for the licentiate thesis of Johan Löfberg, Linköpings universitet.

Kent Hartman participated in the Reference group for the development of the engineering program Karlstad University, January 11 and 12, April 26 and October 3. He visited the "Scanautomaticmässan" in Stockholm on November 21. He has also visited several high schools in the region to develop contacts with Linköping University.

Ola Härkegård participated in the Russian - Swedish Control Conference, Moscow, Russia, 12-16 May 2001, in the 5th IFAC Symposium Nonlinear Control Systems, Saint-Petersburg, Russia, 4-6 July 2001, and in the European Control Conference, Porto, Portugal, 4-7 September 2001.

Rickard Karlsson participated in the American Control Conference, Arlington, USA, 25-27 June 2001 and in IEE International Seminar on Target Tracking, Enschede, The Netherlands, 16-17 October 2001.

Sunil Kukreja participates in the ERNSI Workshop, Cambridge, Great Britain 17 - 19 September 2001.

David Lindgren Visited the Center for System Engineering and and Applied Mechanics (CESAME) at Louvain-la-Neuve University, Belgium, 14-16 November 2001.

Lennart Ljung took part in the Symposium on cooperation between industry and academia, organized by the Swedish-French Research Organization (ASFSR) in Nice, April 23, 2001. He then took part in the Fourth Russian-Swedish Conference Control in Moscow, May 13 - 17. He participated in the 18th IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, May 21- 23. On August 13 - 16 he participated in the SIAM Conference on Linear Algebra in Boston, MA and September 3 - 7 he took part in the European Conference on Control in Porto , Portugal. He took part in the ERNSI (European Research Network on System Identification) Workshop in Cambridge, England, September 17 - 20 and in the Nordic Matlab Conference in Oslo, October 17 - 18. In November 28 - 29 he participated in the ICCIOS Conference at the VUB, Brussels and then participated in the IEEE Conference on Decision and Control, December 4 - 7, in Orlando, FL.

Johan Löfberg participated in the Russian - Swedish control conference, Moscow, Russia, 12-16 May 2001 and in the European Control Conference, Porto, Portugal, 4-7 September 2001.

Niclas Persson participated in ICASSP (International Conference on Signal and Speech Processing) May 7 - 13 in Salt Lake City, USA and ATTCE in Barcelona, Spain October 1-3. He also attended SAE (Society of Automotive Engineers World Congress), Detroit, MI, March 5-8 2001.

Per-Johan Nordlund participated in the American Control Conference, Arlington, USA, 25-27 June 2001.

Mikael Norrlöf participated in the Third conference on Computer Science and Systems Engineering in Linköping (CCSSE'01), Norrköping, Sweden, March 14-15, 2001, in the 32nd International Symposium on Robotics (ISR), Seoul, Korea, April 19-21, 2001 and in the European Control Conference, Porto, Portugal, September 4-7, 2001.

Wolfgang Reinelt visited Department of Electrical and Computer Engineering, University of Newcastle, Australia, 5-17 January 2001 and participated in European Control Conference, Porto, Portugal, 4-7 Sept 2001.

Jacob Roll participated in the ERNSI meeting, Cambridge, UK, 17-19 September and in the 40th IEEE Conference on Decision and Control, Orlando, USA, 4-7 December 2001.

Ulla Salaneck participated in the Russian - Swedish Control Conference, Moscow, Russia, 12-16 May 2001, and in the 10th ERNSI Workshop, Cambridge, England, 17-19 September 2001.

Fredrik Tjärnström visited Department ELEC, Vrije University, Brussels, Belgium, 8-18 January 2001 and Dipartimento di Ingegneria dell'Informazione, University of Siena, Italy, 17-27 April 2001. He participated in the Russian - Swedish control conference, Moscow, Russia, 12-16 May 2001, and in the European Control Conference, Porto, Portugal, 4-7 September 2001, and in the 10th ERNSI Workshop, Cambridge, England, 17-19 September 2001.

Måns Östring participated in the 32nd International Symposium on Robotics, Seoul, Korea, 19-21 April.

Appendix F

Lectures by the Staff

- Jonas Elbornsson: *Tutorial together with Ericsson Microelectronics: Data converters for Telecommunication* IEEE International Conference on Electronics, Circuits and Systems, Malta, September 2-5 2001.
- Torkel Glad: *Structure of nonlinear systems and linear algebra* Plenary talk, IFAC Symposium on System Structure and Control, Prague, August 31.
- Torkel Glad: *Some Structural Properties of Control Systems Revealed by Differential Algebra*, Russian-Swedish Control Conference, Moscow, May 16.
- Fredrik Gunnarsson: *Resource Management for Wireless Communications* Third Conference in Computer Science and Systems Engineering, Norrköping, Sweden, March 15, 2001.
- Fredrik Gunnarsson: *Fundamental Limitations of Power Control in WCDMA* Vehicular Technology Conference, Atlantic City, NJ, USA, October 8, 2001.
- Svante Gunnarsson: *On regulator stability in control of flexible mechanical systems*, 32nd International Symposium on Robotics, Seoul, Korea, 20 April, 2001.
- Fredrik Gustafsson: *Particle filters for positioning*, Chalmers , 8 February, 2001.

- Fredrik Gustafsson: *The LiTH Matlab course* Chalmers , 8 February, 2001.

- Fredrik Gustafsson: *Virtual sensors of tire pressure and road friction*, Society of Automotive Engineers World Congress, Detroit, 7 March, 2001.

- Fredrik Gustafsson: *Sensor fusion for accurate computation of yaw rate and absolute velocity*, Society of Automotive Engineers World Congress, Detroit, 7 March, 2001.

- Fredrik Gustafsson: *Stochastic observability and fault diagnosis of additive changes in state space models*, International Conference on Signal and Speech Processing (ICASSP), Salt Lake City, May, 2001,

- Fredrik Gustafsson: *Current activities in communication research* KTH, 15 May, 2001.

- Fredrik Gustafsson: *Model-based anti-spin control* Workshop on Hybrid methods for Control (H2C), Berlin, 8 June, 2001.

- Anders Hansson: *A Primal-Dual Potential Reduction Method for Integral Quadratic Constraints* American Control Conference, Arlington, Virginia, USA, June 26, 2001.

- Anders Hansson: textslEfficient Implementations of Interior-Point Methods for Integral Quadratic Constraints Fourth SIAM Conference on Linear Algebra in Singals, Systems and Control, Boston, Massachusetts, USA, August 15, 2001.

- Lennart Ljung: *System Identification with Applications to Vibration Analysis* Svenska Vibrationssällskapets Konferens, Stockholm, May 11, 2001.

- Lennart Ljung: *Aspects on the Interpretation of Disturbances in System Identification* Fourth Russian-Swedish Conference on Control, Moscow, Russia, May 16, 2001

- Lennart Ljung: *Black Box Models from Input-Output Models* State of the Art Lecture at the 18th IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, May 21, 2001.

- Lennart Ljung: *Numerical Linear Algebra in System Identification*, SIAM Conference on Linear Algebra in System Identification, Boston, USA, August 14, 2001.
- Lennart Ljung: *Estimating Linear Time-invariant Models of Nonlinear Time-varying Systems*, The Workshop in Honor of Torsten Bohlin, Royal Institute of Technology, Stockholm, August 31, 2001.
- Lennart Ljung: *Estimating Linear Time-invariant Models of Nonlinear Time-varying Systems*, Semi-plenary Lecture at the European Control Conference, ECC'01, Portu, Portogal, September 7, 2001.
- Lennart Ljung: *From Data to Model - System Identification from the Engineers Perspective* The Nordic Matlab Conference, Oslo, Norway, October 18 2001.
- Lennart Ljung: *Estimation of Linear Time-invariant Models, as Approximations of General Systems*, The ICCOS-IEUAP Conference, VUB, Brussels, November 28, 2001.
- Lennart Ljung: *Robustness Guarantees for Linear Control Designs with an Estimated Non-linear Model-error Model* The 31th IEEE Conference on Decision and Control, Orlando, FL, USA, December 6, 2001.
- Lennart Ljung: *Robust High Gain DENN Observer for Nonlinear Stochastic Continous Time Systems*, The 31th IEEE Conference on Decision and Control, Orlando, FL, USA, December 6, 2001.
- Johan Löfberg: *Robust MPC synthesis* Mid Sweden University, Sweden, 7 November, 2001.
- Johan Löfberg: *Minimax MPC for systems with uncertain input gain - revisited* Russian - Swedish control conference, Moscow, Russia, 14 May, 2001.
- Johan Löfberg: *Nonlinear receding horizon control: Stability without stabilizing constraints.* European Control Conference, Porto, Portugal, 7 September 2001.
- Mikael Norrlöf: *Iterative Learning Control – in theory and practice.* Seminar at Department of Signals, Sensors and Systems, Royal Institute of Technology (KTH), Stockholm, Sweden, March 8, 2001.

- Mikael Norrlöf: *Comparative study on first and second order ILC – frequency domain analysis and experiment* CCSSE'01, Norrköping, Sweden, March 14, 2001.

- Mikael Norrlöf: *An adaptive approach to Iterative Learning Control – with experiments on an industrial robot* ECC 2001, Porto, Portugal, September 4, 2001.

- Mikael Norrlöf: *Robot trajectory generation* Seminar at Dep. of E.E., Linköpings universitet, Linköping, Sweden, November 22, 2001.

- Niclas Persson: *Event Based Sampling with Application to Vibration Analysis in Pneumatic Tires* ICASSP 01, Salt Lake City, USA, May 13, 2001.

- Niclas Persson: *Low Tire Pressure Warning System* ATTCE 01, Barcelona, Spain, May 2, 2001.

- Wolfgang Reinelt: *Aspects of analysis and design of saturation-avoiding controllers.* Dept of Electrical and Computer Engineering, University of Newcastle, Australia. 15 January 2001.

- Wolfgang Reinelt: *Some aspects of identification for control.* ABB Corporate Research, Baden-Dättwil, Switzerland. 20 June 2001.

- Wolfgang Reinelt: *Robust control of identified models with mixed parametric and non-parametric uncertainties.* European Control Conference, Porto, Portugal, 7 Sept 2001.

- Wolfgang Reinelt: *Control of Multivariable Systems with hard constraints.* European Control Conference, Porto, Portugal, 6 Sept 2001.

- Wolfgang Reinelt: *Robust control of SISO systems with hard input constraints.* European Control Conference, Porto, Portugal, 5 Sept 2001.

- Wolfgang Reinelt: *Design of optimal control systems with bounded control signals.* European Control Conference, Porto, Portugal, 4 Sept 2001.

- Jacob Roll: *Some methods for identification and robust verification of piecewise affine systems* Chalmers University of Technology, Sweden, 12 January, 2001.

- Fredrik Tjärnström: *Model reduction and variance reduction* University of Siena, Italy, 24 April, 2001.

- Fredrik Tjärnström: *Variance properties of a two-step ARX estimation procedure* Russian - Swedish control conference, Moscow, Russia, 14 May, 2001.

- Fredrik Tjärnström: *Variance properties of a two-step ARX estimation procedure.* European Control Conference, Porto, Portugal, 6 September 2001.

- Fredrik Tjärnström: *Variance properties of a two-step ARX estimation procedure* 10th ERNSI Workshop, Cambridge, England, 18 September, 2001.

Appendix G

Publications

Licentiate Theses

[1] Johan Löfberg. Linear model predictive control: Stability and robustness. Licentiate Thesis no. 866, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2001.

[2] Ola Härkegård. Flight control design using backstepping. Licentiate Thesis no. 875, Department of Electrical Engineering, Linköpings universitet, SE-581 83 Linköping, Sweden, Mar 2001.

[3] Jonas Elbornsson. Equalization of distortion in A/D converters. Licentiate Thesis no. 883, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Apr 2001.

[4] Jacob Roll. Robust verification and identification of piecewise affine systems. Licentiate Thesis no. 899, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Sep 2001.

[5] Ingela Lind. Regressor selection in system identification using ANOVA. Licentiate Thesis no. 921, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Nov 2001.

Journal Papers and Book Chapters

[6] Anders Stenman and Fredrik Gustafsson. Adaptive smoothing methods for frequency-function estimation. *Automatica*, 37(5):675–685, May 2001.

[7] Mikael Norrlöf and Svante Gunnarsson. Disturbance aspects of iterative learning control. *Engineering Applications of Artificial Intelligence*, 14(1):87–94, Jan 2001.

[8] Fredrik Gunnarsson, Fredrik Gustafsson, and Jonas Blom. Dynamical effects of time delays and time delay compensation in power controlled DS-CDMA. *IEEE Journal on Selected Areas in Communications*, 19(1), Jan 2001.

[9] Torkel Glad and A. J. Isaksson. Bounds on the response time under control constraints. *Automatica*, 37:2073–2076, Nov 2001.

[10] Lennart Ljung. Estimating linear time invariant models of non-linear time-varying systems. *European Journal of Control*, 7(2-3):203–219, Sept 2001. Semi-plenary presentation at the European Control Conference, Sept 2001.

[11] Krister Edström and Torkel Glad. Algorithmic, physically based mode initialization when simulating hybrid systems. *Journal of Systems and Control Engineering*, Dec 2001.

[12] M. Gevers, Lennart Ljung, and P Van den Hof. Asymptotic variance expressions for closed-loop identification. *Automatica*, 37(5):781–786, May 2001.

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[14] A. S. Poznyak and Lennart Ljung. On-line identification and adaptive trajectory tracking for nonlinear stochastic continuous time systems using differential neural networks. *Automatica*, 37(8):1257–1268, Aug 2001.

[15] Fredrik Gunnarsson and Fredrik Gustafsson. Time delay compensation in power controlled cellular radio systems. *IEEE Communications Letters*, 5(7), Jul 2001.

[16] Wolfgang Reinelt. Loop shaping of multivariable systems with hard constraints on the control signal. *Electrical Engineering*, 83(4):169–177, 2001.

[17] L. Xie and Lennart Ljung. Asymptotic variance expressions for estimated frequency functions. *IEEE Trans. Automatic Control*, AC-46(12):1887 – 1899, Dec 2001.

[18] Svante Gunnarsson and Mikael Norrlöf. On the design of ILC algorithms using optimization. *Automatica*, 37:2011–2016, Dec 2001.

[19] M. W. Braun, D. Rivera, and Anders Stenman. A 'model-on-demand' identification methodology for non-linear process systems. *Int. J. Control*, 74(18):1708–1717, Dec 2001.

Conference Papers

[20] D.Lawesson, U.Nilsson, and Inger Klein. Model-checking based fault isolation in UML. In *12th International Workshop on Principles of Diagnosis*, pages 103–110, Sansicario, Italy, Mar 2001.

[21] Johan Löfberg. A convex relaxation of a minimax MPC controller. In *Third Conference on Computer Science and Systems Engineering in Linköping, 2001*, Feb 2001.

[22] Ola Härkegård. Backstepping designs for aircraft control - what is there to gain? In *Proc. of the Third Conference on Computer Science and Systems Engineering in Linköping*, pages 201–205, Norrköping, Sweden, Mar 2001.

[23] Per-Johan Nordlund and Fredrik Gustafsson. Recursive state estimation of nonlinear systems. In *Proceedings of the third conference on Computer Science and Systems Engineering in Linköping*, pages 175–181, Mar 2001.

[24] Mikael Norrlöf. Comparative study on first and second order ILC – frequency domain analysis and experiments. In *Proceedings of the Third conference on Computer Science and Systems Engineering in Linköping*, pages 37 – 44, Mar 2001.

[25] Måns Östring. Closed loop identification of the physical parameters of an industrial robot. In *Third conference on Computer Science and Systems Engineering in Linköping*, pages 191–198, Mar 2001.

[26] Fredrik Gustafsson, Fredrik Gunnarsson, Niclas Bergman, Urban Forssell, Jonas Jansson, Rickard Karlsson, and Per-Johan Nordlund. A framework for particle filters for positioning, navigation and tracking. In *Proc. of the 11th IEEE Signal Processing Workshop on Statistical Signal Processing* 2001.

[27] Erik Geijer Lundin and Fredrik Gunnarsson. Admission control in WCDMA based on relative load estimates. In *Towards 4G and Future Mobile Internet, Proc. Nordic Radio Symposium*, Nynäshamn, Sweden, apr 2001.

[28] Erik Geijer Lundin and Fredrik Gunnarsson. Admission control in cellular radio systems based on relative load estimates. In *Third Conference on Computer Science and Systems Engineering in Linköping*, pages 163–168, Mar 2001.

[29] Frida Gunnarsson, Fredrik Gunnarsson, and Fredrik Gustafsson. TCP performance based on queue occupation. In *Third Conference on Computer Science and Systems Engineering, CCSSE 01*, pages 127–134, Mar 2001.

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[31] Anna Hagenblad and Inger Klein. Teaching control theory using problem based learning. In *12th EAEEIE Annual Conference on Innovations in Education for Electrical and Information Engineering*, Nancy, France, May 2001.

[32] Johan Löfberg. Nonlinear receding horizon control: Stability without stabilizing constraints. In *Proceedings of the European Control Conference ECC01, Porto, Portugal*, Apr 2001.

[33] Jacob Roll. Identification of piecewise affine Wiener models via mixed-integer programming. In *Third Conference on Computer Science and Systems Engineering in Linköping*, pages 297–304, Norrköping, Sweden, Mar 2001.

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[35] Rickard Karlsson and Fredrik Gustafsson. Range estimation using angle-only target tracking with particle filters. *Proc. of the American Control Conference*, pages 3743–3748 Arlington, Virginia, Jun 2001.

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[37] Mikael Norrlöf. An adaptive approach to iterative learning control with experiments on an industrial robot. In *European Control Conference, ECC 2001*, Seminário de Vilar, Porto, Portugal, Sep 2001.

[38] Per-Johan Nordlund and Fredrik Gustafsson. Sequential Monte Carlo filtering techniques applied to integrated navigation systems. In *Proceedings of the American Control Conference*, June 2001.

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[40] Wolfgang Reinelt and Lennart Ljung. Robust control of identified models with mixed parametric and non-parametric uncertainties. In *Proc. of the European Control Conference*, pages 3564–3569, Porto, Portugal, Sep 2001.

[41] Wolfgang Reinelt. Design of optimal control systems with bounded control signals. In *Proc. of the European Control Conference*, pages 348–353, Porto, Portugal, Sep 2001.

[42] Wolfgang Reinelt and M. Canale. Robust control of siso systems subject to hard input constraints. In *Proc. of the European Control Conference*, pages 1536–1541, Porto, Portugal, Sep 2001.

[43] Wolfgang Reinelt. Control of multivariable systems with hard constraints. In *Proc. of the European Control Conference*, pages 2576–2581, Porto, Portugal, Sep 2001.

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association using Monte Carlo methods, IEE International Seminar on Target Tracking: Algorithms and Applications, Enschede, The Netherlands, Oct 2001.

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Appendix H

Technical Reports

[66] Johan Löfberg. Yalmip: A matlab interface to SP, MAXDET and SOCP. Technical Report LiTH-ISY-R-2328, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2001.

[67] Johan Löfberg. A stabilizing MPC algorithm using performance bounds from saturated linear feedback. Technical Report LiTH-ISY-R-2327, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan 2001.

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[70] Fredrik Gunnarsson, Fredrik Gustafsson, and Jonas Blom. Estimation and outer loop power control in cellular radio systems. Technical Report LiTH-ISY-R-2332, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb 2001.

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Appendix I

Master Theses (Examensarbeten)

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