LINKÖPING UNIVERSITY
DIVISIONS OF AUTOMATIC CONTROL AND COMMUNICATION SYSTEMS
ACTIVITY REPORT
2000

Contents

Chapter 1

Introduction

This is the first joint annual report from the Divisions of Automatic Control and Communication Systems. The Division of Communication Systems within the Department of Electrical Engineering was created at the beginning of the year 2000 with Professor Fredrik Gustafsson as Division Head. We have decided to keep close links between the divisions, due to the proximity of research tools and the social contacts between the faculty and PhD students. The joint Annual report and the joint web page are examples of these close links.

The two divisions consists of some thirty people. We teach thirteen undergraduate courses to more than eleven hundred students. The courses cover both traditional control topics and more recent topics in model building and signal processing.

Our research interests are focused on the following areas:

- *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 Robotics Products.

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

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

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

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 Fredrik Gunnarsson, Valur Einarsson and Mikael Norrlöf defended their Ph.D.-theses and Fredrik Tjärnström and Christina Carlsson defended their Lic. Eng. degree.

During the year four of our funding agencies have evaluated our performance: TFR evaluated all TFR-funded research in the area of Signals and Systems in September. The findings are reported in

Signals and Systems in Sweden, TFR Evaluation Programme, Volume 6, December 2000

NUTEK evaluated all their competence centra during the year and ISIS was scrutinized in September. The results are reported in

> *The NUTEK Competence Centres Programme: Second Mid-Term International Evaluation, Group 3, NUTEK R 2000:21, September 2000*

Moreover, the ECSEL Board ordered an international evaluation of the research activities of ECSEL, and the EU TMR-programme evaluated ERNSI (European Research Network on System Identification), of which we are one partner in September. All these evaluations turned out to be very favorable for us, and excerpts of the texts can be found on our home page.

In the following pages the main research results obtained during 2000 are summarized. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge, most easily from our web-site.

We invite you to visit our home page:

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

The competence center ISIS has the home page

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

and for the research school ECSEL turn to

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

Chapter 2

Network Services

There are a number of ways you can access the work produced at this group. Most convenient is probably electronic mail to the person you wish to contact. The email addresses are listed at the end of this activity report. Apart from these, shorter but quite arbitrary email addresses you can always use the general form: `FirstName.LastName@isy.liu.se`, e.g. `Lennart.Ljung@isy.liu.se`.

We also have a generic email address:

`Automatic.Control@isy.liu.se`

or `AC@isy.liu.se` for short. Emails sent to this address are currently sent to our secretary Ulla.

Finally you can also retrieve reports and software electronically either by using our FTP- or World Wide Web- services. This is our preferred method of distributing reports.

2.1 World Wide Web

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

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

When you surf around in our WWW-environment you will find some general information over this group, the staff, seminars, information about undergraduate courses taught by the group and you will get the opportunity the bring home technical reports produced at this group. This is the easiest way to access the group's work, just click and collect.

Our WWW service is always under development. We look forward to your feedback regarding this service. If you have any questions or comment, please send an email to our research engineer, 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.

2.3 Anonymous FTP

We also have an anonymous ftp server. If you have access to a windows based ftp program such as `ftptool` this is a very nice way of having direct access to reports and software. The basic address is:

`ftp.control.isy.liu.se (130.236.50.10)`

Or if you prefer to use you webbrowser for FTP:

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

The basic file structure is:

`/pub:  Reports Software Misc`

Below this point it is self instructing. Do not forget to use the binary transfer mode when you get compressed files.

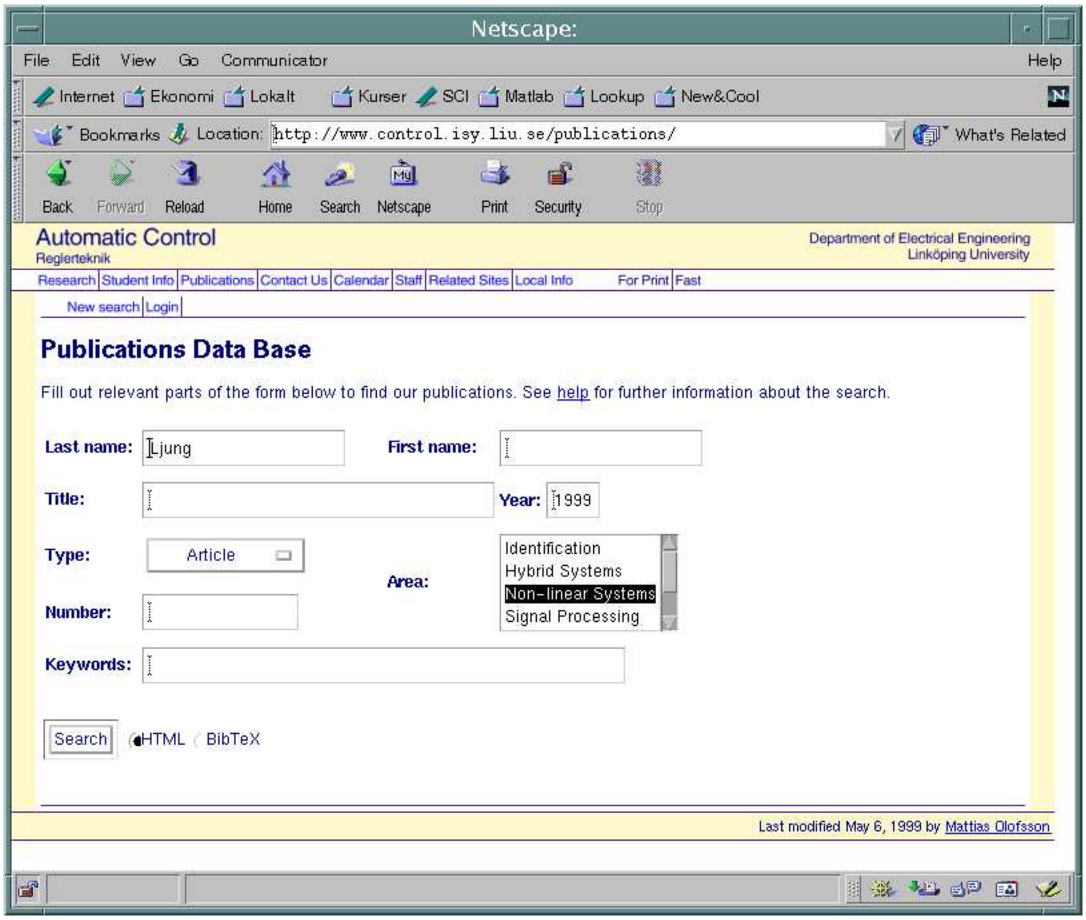


Figure 2.1: The publications data base interface

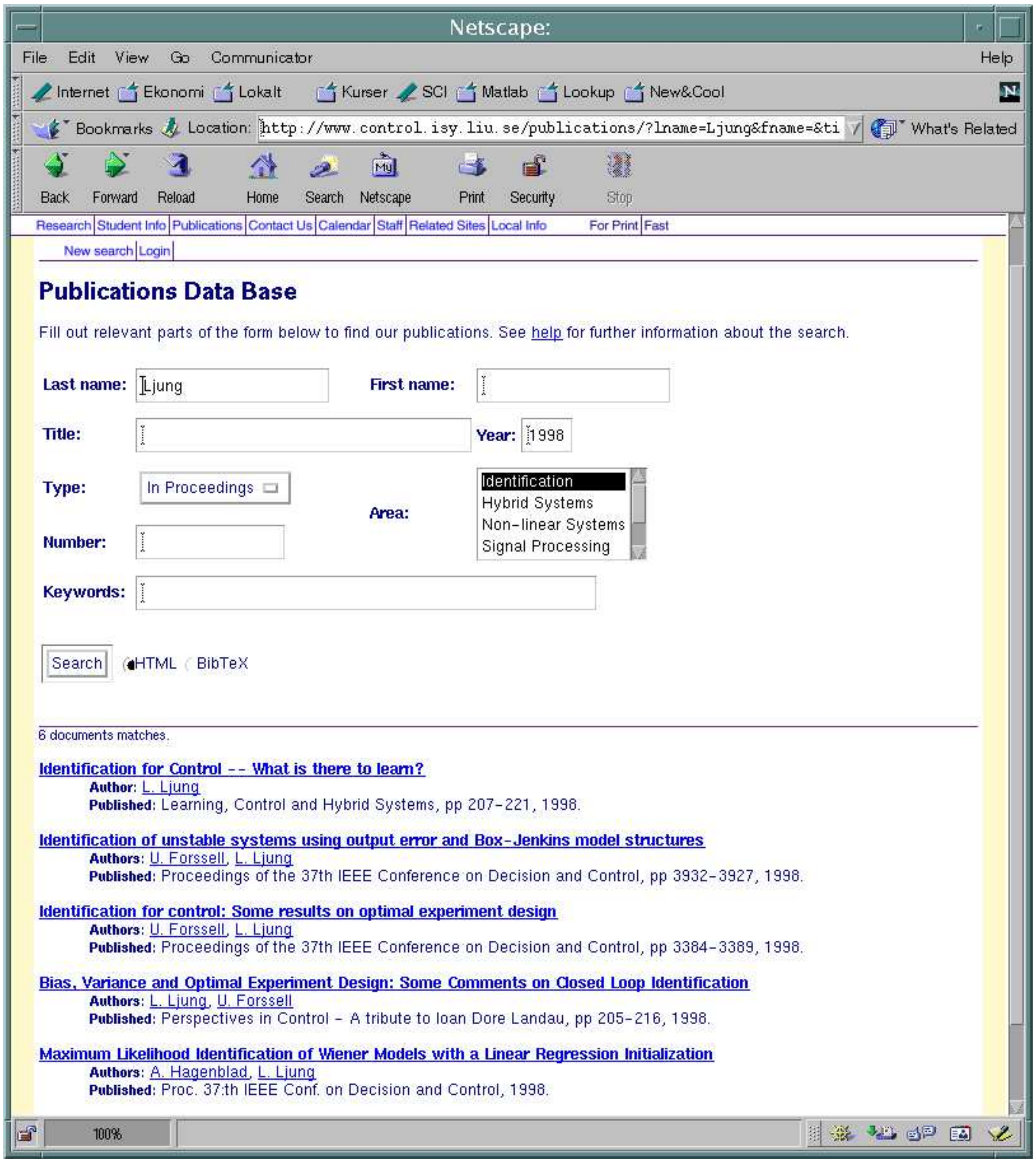


Figure 2.2: Example of search result

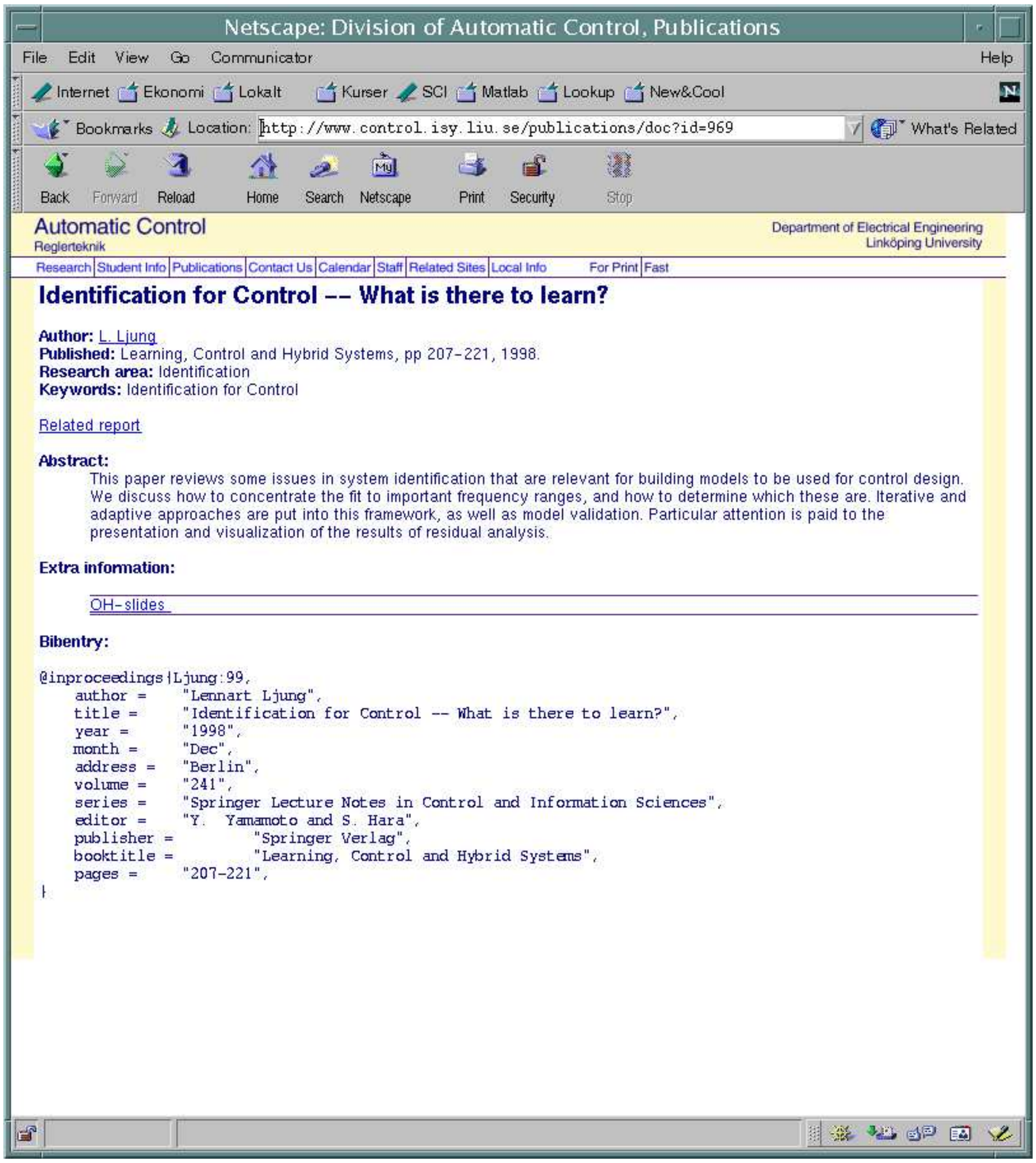


Figure 2.3: Example of a publication home page

Chapter 3

System Identification

3.1 Introduction

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

During 2000 a licentiate thesis, [4], was finished.

3.2 Identification of Wiener models

A Wiener model consists of a linear dynamic system followed by a static nonlinearity. The input and output of the total system can be measured, but not the intermediate signal. Wiener models arise in practice whenever a measurement device has a nonlinear characteristics. In chemistry, pH control systems can be described as a Wiener model.

If the Wiener system contains process noise, i.e., noise entering before the nonlinearity, the predictor is difficult to express, so the true prediction error method cannot be used. It may then be interesting to use an approximative prediction error method, disregarding the process noise. That this method may produce biased estimates was shown in [76].

In the case with both process noise and measurement noise, the Maximum Likelihood estimate of the parameters can be derived. In [37], it was shown that the estimate can be computed, and that it gives an unbiased estimate in a simulation where the approximative prediction error estimate is heavily biased.

3.3 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.

During 2000 we have studied some different aspects of the closed-loop identification problem. This has resulted in the articles, [6, 7, 9]

3.4 Model 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.

For the modeling part of model-on-demand we have adopted a weighted regression approach, where a weight sequence $w_k(\cdot)$ is introduced to localize the estimation around some operating point $\varphi(t)$, i.e.,

$$\hat{\theta}_t = \arg\min_{\theta} \sum_k \{y(k) - g(\varphi(k), \theta)\}^2 \cdot w_k(\varphi(t))$$

Two conceptually different approaches for weight selection has been investigated, where the first is based on traditional kernel assumptions and the other relies on an explicit optimization stage. In the 1999 PhD thesis by Anders Stenman two algorithms corresponding to these approaches were presented. Applications of these idear to model predictive control are described in [17] and [22]. Applications to model error modeling are given in [15], and ideas for regressor selction are discussed in [16].

The second application addresses the frequency-domain identification problems that occur when estimating spectra of time series or frequency responses of linear systems. In [10] we show that the model-on-demand concept provides a very good way of estimating such quantities using automatic, adaptive and frequency-dependent choices of frequency resolution. This gives several advantages over traditional spectral analysis techniques.

3.5 Bootstrap Techniques

Bootstrap is a resampling technique developed to calculate uncertainties in estimates. The motivation for bootstrap is that asymptotic results describing the uncertainty of the estimate is not always applicable since only few data might be available. It could also be the case that there are no results whatsoever about the distribution of the estimate, making it difficult to judge the quality of the estimate.

Bootstrap can be said to perform Monte Carlo simulations from an estimate of the distribution from which the data is generated, i.e., given independent identically distributed samples $x_1, \dots, x_N$ from a (unknown) distribution $F_X(x)$, estimate this distribution by

$$\hat{F}_X(x) = \frac{\#\{x_i \leq x\}}{N}.$$

Generate several sets of bootstrap resamples from $\hat{F}_X(x)$ according to

$$\{x_1^*, \ldots, x_N^*\}$$

and use these resampled values as if they were generated from $F_X(x)$.

This idea can be used in system identification related problems where the distribution of the estimate is unknown, for example in case of undermodeling. This topic is discussed in [4], where it is shown how to use bootstrap to come up with very reliable estimates of the variance error in undermodeled models. Bootstrap can also be applied to describe uncertainties in other system identification problems.

The problem of computing uncertainty regions of simultaneous confidence degree is described in [32]. Here it is shown how bootstrap can be used to come up with reliable simultaneous uncertainty regions without too much computional effort.

3.6 Model Validation, Model Error Modeling and Control Design

The validation of an identified model is a crucial step in System Identification, as it directly links to robust control design and hence, to one of the major areas of application of System Identification. One way or another, most validation techniques are based on analysis of the **residuals**

$$\varepsilon(t) = y(t) - \hat{y}(t|\hat{\theta}_N)$$

where $\hat{y}(t|\hat{\theta}_N)$ is the predicted output, based on the chosen model $\hat{\theta}_N$. Traditional statistical techniques include correlation analysis of these residuals, as well as analyzing the cross correlation with past inputs. One way of obtaining such models is to use nonparametric methods. The possible advantage of this approach is that it is in some sense the best unprejudiced estimate of the model error. The method is described in [15].

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 [70], we discuss and compare three approaches to System Identification, that explicitly aim at separating these contributions: Goodwin's 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.

In [27] 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 periodic inputs, and how to deal with non-linear error models.

In [79] we discuss what results about the quality of an estimated model can be achieved, if no probabilistic assumptions are introduced (the so-called "unknown-but-bounded approach"). Several technical results that illustrate possibilities and difficulties are also given. A related approach exists, where Set Membership techniques are embedded into a Model Error Modeling framework, based on residual analysis. It is shown how the computation of the minimum noise bound for which a nominal model is not falsified by i/o data, can be used as a rationale for selecting an appropriate model class in the set membership setting.

3.7 Aspects on Identification Methods

Missing Data

Situations where data samples are missing are quite common. This may be both input and output signals. In [45] we describe and approach to deal with this problem, that is based on simple ARX models.

Subspace Methods

To find good or optimal choices of design variables in so called subspace identification methods is an important current problem. Several results of this kind are discussed in [59, 60, 61, 81].

Structure Determination Using Variance Analysis

The use of Variance Analysis to determine which regressors to include in non-linear black box models, such as neural networks, is discussed in [28]. It is shown that this may lead to much improved efficiency, and also to better structure decisions, than estimating all the possible structure combinations.

Fuzzy Models

Sometimes there may be prior information about a system that is not easily incorporated in a standard parametric model. For a non-linear system it could, e.g., be that the steady state output level is monotonically increasing with the input level. In [8] it is show how fuzzy modeling/estimation techniques can be used to take care of such prior information.

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 [4] and [31]. 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 other cases we get the same variance as the direct estimation would have given.

Chapter 4

Non-linear and Hybrid Systems

4.1 Constraints and Structures in Dynamic Systems

4.1.1 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 in [52] 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

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

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].

4.1.2 Identifiability and Inequalities

When modeling physical systems one often arrives at a mixture of equations in a number of physical variables and their derivatives. The model might only be valid for certain values of the physical variables or one might want to study it only in a certain range. This could be expressed by inequalities or inequations. An obvious question is then whether there exists a solution that satisfies all equations, inequations and inequalities. Also one would like to transform the system to some standard form which facilitates the computation of such a solution. In [38] identifiability is considered in this framework. The system

$$\dot{y}\ddot{y} + \theta^2 y = 0$$

for instance, is not globally identifiable, since the sign of θ can not be determined. Suppose it is known that $\theta > 0$. One could then phrase the identifiability question as follows. Does there exist a solution of the system

$$\begin{aligned}
\dot{y}\ddot{y} + \theta_a^2 y &= 0 \\
\dot{y}\ddot{y} + \theta_b^2 y &= 0 \\
\dot{\theta}_a = 0, \quad \dot{\theta}_b &= 0 \\
\theta_a - \theta_b &\neq 0 \\
\theta_a > 0, \quad \theta_b &> 0
\end{aligned}$$

After some algebraic manipulations this is shown to be equivalent to

$$\begin{aligned}
\dot{\theta}_a = 0,\ \ \theta_a + \theta_b = 0,\ \ \dot{y}\ddot{y} + \theta_a^2 y &= 0 \\
\dot{y} \neq 0,\ \ \theta_a &\neq 0 \\
\theta_a > 0, \quad -\theta_a &> 0
\end{aligned}$$

which lacks solution, since $\theta_a > 0$ and $-\theta_a > 0$ are incompatible. The original system is thus identifiable under the constraint $\theta > 0$.

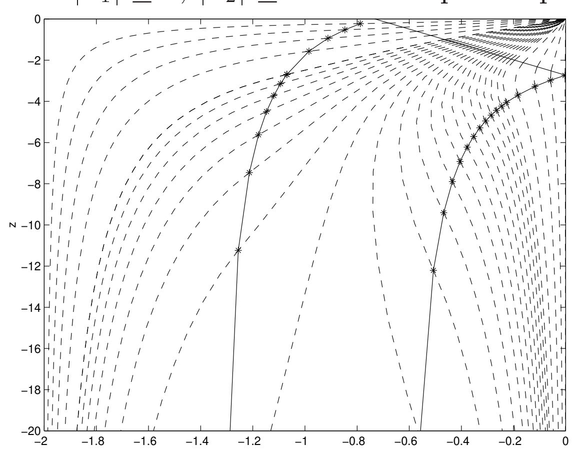
These concepts can be applied to the analysis of identifiability of internal combustion engines. In [11] the identifiability of different parts of a car engine model are discussed. In particular the effect of adding or removing sensors and of varying a priori information is investigated.

4.1.3 Control under Constraints

In many control problems the actuator constraints can be described as bounds on both control amplitude and control rate of change. If the open loop system is unstable, such constraints limit the region of the state space where stabilization is possible. An application where this occurs is pitch axis control of modern aircraft. In many cases the stabilization is further complicated by the fact that some actuators are shared with the lateral control. A large manoeuvre in e.g. roll will therefore decrease the actuator range which is available for stabilization in pitch. The problem can also be analyzed using linear quadratic control with amplitude constraints on the control. A simplified problem

$$\begin{aligned} \dot{x} &= x + u_1 + u_2 \\ \dot{x}_\ell &= -x_\ell + u_1 - u_2 \end{aligned}$$

with one unstable mode and one stable mode together with the control constraint $|u_1| \leq 1$, $|u_2| \leq 1$ has the optimal phase plane shown below



The triangular region to the upper right is the part where the solution coincides with the ordinary unconstrained linear quadratic control law. In the region to the left the control is $u_1 = 1$, $u_2 = 1$. In the middle region it is $u_1 = 1$, u_2 unconstrained, while in the right region it is $u_1 = 1$, $u_2 = -1$. The dashed curves are the optimal trajectories.

4.1.4 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. 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.

4.1.5 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 [38] many of the aspects concerning the use of quantifier elimination and other algebraic methods in control are described.

4.2 Nonlinear Design methods

4.2.1 IQC synthesis based on inertia constraints

Integral quadratic constraints (IQCs) can be used for proving stability of systems with uncertainties and nonlinearities. Similarly, IQCs can also be used for controller synthesis. Necessary and sufficient conditions for the existence of such a controller are derived. These conditions include linear matrix inequalities (LMIs) and matrix inertia specifying the number of negative eigenvalues of a matrix. In general, these conditions are non-convex. Connections to bilinear matrix inequalities and LMIs with rank constraints are also discussed.

4.2.2 Stability of Slowly Varying Systems

Many control application involve systems that are time varying. Consider for instance an aircraft or a ship, which both have dynamics that depend on their speed. The rate of change of speed, that is the acceleration, is limited and can be considered as a parameter that is slowly varying. The parameter dependent part is localized to an "uncertainty" block, Δ, while the remaining system, M is assumed to be linear and time invariant, see Figure 4.1

In order to analyze such a system we can approach the problem using Lyapunov functions.

The Lyapunov method is based on a Lyapunov function, $V = x^T P x$, with an LFT parameterization:

$$P(\Delta) = T(\Delta)^T Q T(\Delta)$$

where $T(\Delta) = \hat{D} + \hat{C}\Delta(I - \hat{A}\Delta)^{-1}\hat{B}$.

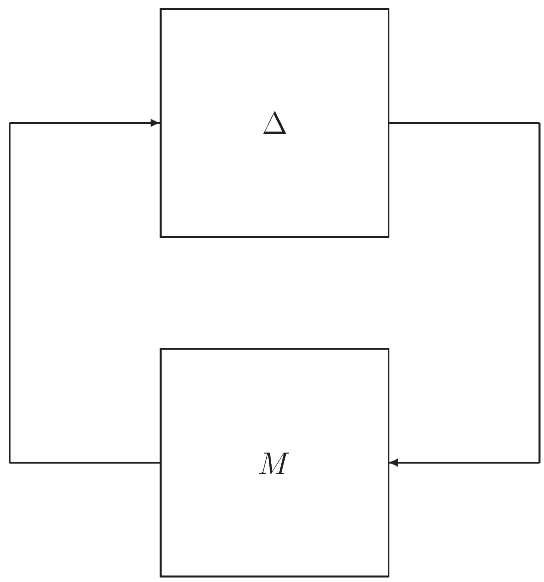


Figure 4.1: System with slowly varying uncertainties. The Δ block is assumed to be parameter dependent, while M is a linear time-invariant system. We assume that both Δ and its derivative, $\dot{\Delta}$, are bounded.

This structure is quite flexible and includes the affine parameterization, which is common in the literature.

The IQC approach is based on the swapping lemma, which essentially states that

$$\Delta T(s) = T(s)\Delta + U(s)\dot{\Delta}V(s),$$

where T, U and V are appropriate chosen linear operators.

Both methods involve linear matrix inequalities (LMIs).

4.2.3 Applications of backstepping

Backstepping is a method for design of nonlinear state feedback by successive extensions of a Lyapunov function in order to guarantee stability. Applications to aircraft control are considered in [57, 72, 73, 21]. It is shown that the aircraft dynamics after some approximations, can be written in the form required for backstepping. Both pitch attitude and flight angle control are considered. In [39] it is shown how input nonlinearities and uncertainties can be handled. approximations, can be written in the form required for backstepping.

4.2.4 Model Predictive Control

In Model Predictive Control (MPC) an optimal control problem over a finite horizon is solved. To guarantee stability one can introduce terminal constraints. In [64]this problem is considered. A stabilizing algorithm using performance bounds from saturated linear feedback is presented in [42]. Connections to backstepping are considered in [43].

4.2.5 Design Methods for Internal Combustion Engines

In [14] the modeling and identification of flows in internal combustion engines is considered from an entropy point of view.

4.3 Automatic synthesis of sequential control programs

The industry wants provably correct and fast formal methods for handling combinatorial dynamical systems. Despite its importance, fairly little theoretical research has been devoted to this area, and sequential control programs are still created manually without much support for a systematic approach. We propose a method to create sequential control programs automatically and on-line upon request, for example when a plant fault has occurred. The main idea is to spend some effort off-line on *modeling* the process, and from this model generate the control strategy, *i.e.* the *plan*. A provably correct and efficient, polynomial time, planning tool and its application to a miniature assembly line for toy cars is presented in [65].

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).

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 has 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 show 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 Dynamics. The project aims at using particle filters for target tracking, where the non-linear dynamics of the highly manoeuvring objects are essential to catch in a model. Extensions of the well-known IMM algorithm is published in [44].

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.

5.2.1 Particle filters for target tracking

The project aims at using recursive Monte Carlo methods, or particle filters for target tracking, where the non-linear dynamics of a highly maneuvering object are essential to catch in a model. Extensions of the resent published method Auxiliary Particle Filter of Pitt and Shepard 1999, incorporating multiple models and hard constraints is compared to a traditional approach using the the well-known Interacting Multiple Model (IMM) algorithm, [44]. In Figure 5.2.1 a particle cloud together with its position probability density is presented for a radar tracking application.

Non-linear models in state equation and measurement relation and a non-Gaussian noise assumption may lead to non optimal solutions using linearized methods such as the extended Kalman filter (EKF). Moreover, incorporation of constraints to the system parameters is troublesome. The sequential Monte Carlo methods, or particle filters, provide general solutions to many problems where linearizations and Gaussian approximations are intractable or would yield too low performance. The maneuvering target tracking problem is an application which has strong elements of nonlinearity and depending on the application and sensors, the measurement noise may not be well approximated by a Gaussian density.

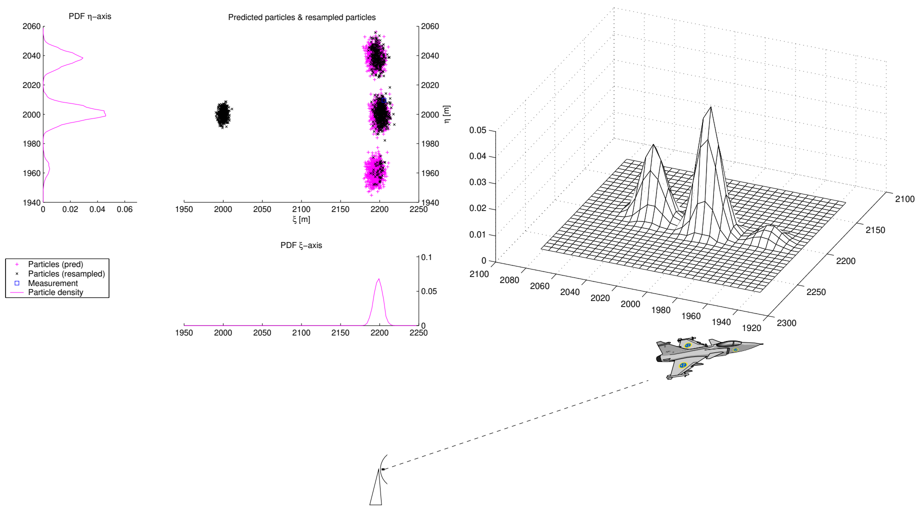


Figure 5.1: Tracking with Auxiliary Particle Filters using a surveillance radar

The sequential Monte Carlo methods, or particle filters provide an approximative Bayesian solution to non-linear discrete time recursive problems by updating an approximative description of the posterior density. Let x_t denote the state of the observed system and $Y_t = \{y_i\}_{i=1}^{t}$ be the set of observations. The method will approximate the density $p(x_t|Y_t)$ by a large set of N particles (state vectors) $\{x_t^i\}_{i=1}^{N}$, where each particle has an assigned probability, w_t^i.

The prediction density $p(x_t|Y_{t-1})$ and filtering density $p(x_t|Y_t)$ for the Bayesian interference is given by

$$\begin{aligned} p(x_t|Y_{t-1}) &= \int p(x_t|x_{t-1})p(x_{t-1}|Y_{t-1})dx_{t-1} \\ p(x_t|Y_t) &\propto p(y_t|x_t)p(x_t|Y_{t-1}) \end{aligned}$$

The main idea is to approximate $p(x_t|Y_{t-1})$ with

$$p(x_t|Y_{t-1}) \approx \frac{1}{N}\sum_{i=1}^{N}\delta(x_t - x_t^i)$$

The recursive solution using particle filters may be implemented using the Bayesian bootstrap or recursive SIR algorithm by Gordon et. al. 1993, or similair methods. The Auxiliary Particle Filter by Pitt and Shepard 1999, is designed to simulate from particles associated with large predictive likelihood. In Figure 5.2.1 a simulation of radar surveillance target tracking is presented. The Auxiliary Particle Filter was extended by conditioning on the traget maneuver and also adopted to handle hard velocity constraints. The position probability density for the target is also shown in the figure.

5.2.2 Particle filters for navigation

This project aims at investigating the integrated navigation problem which involves nonlinear and non-Gaussian estimation for accuracy and integrity monitoring for reliability. A typical configuration for an integrated navigation system is depicted in Figure 5.2.2. The inertial navigation system (INS) is

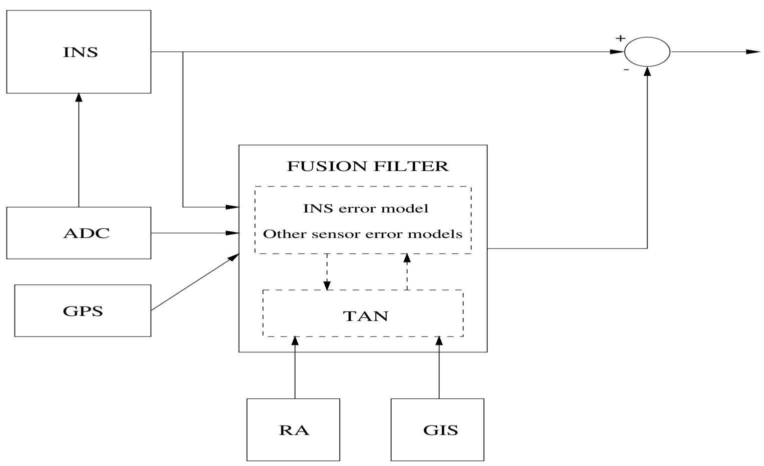


Figure 5.2: An integrated navigation system configuration.

the primary source of navigational data (position, altitude, velocity, attitude, heading, acceleration and angular rate). Small sensor offsets cause the INS data to drift. Terrain aided navigation (TAN) provides a probability density of the position based on measurements from the radar altimeter (RA), air data computer (ADC) and data from the geographical information system (GIS), see Section 5.1. This is used to stabilize the drift by estimating the INS sensor offsets. Note that in a military application the system can not rely on the Global Positioning System (GPS).

The estimation problem consists of online nonlinear and non-Gaussian state estimation, where the states represent the INS errors. An accurate model of the INS drift is nonlinear and requires at least 16 states. Due to the highly nonlinear and non-Gaussian nature of terrain navigation the extended Kalman filter (EKF) is intractable. Sequential Monte Carlo methods (particle filters) provide a solution to the general nonlinear and non-Gaussian problem, see Section 5.2.1. However, a direct application of the particle filter on this high-dimesional problem requires too many particles making the computional load unacceptable. The solution is to isolate the (almost) linear and nonlinear parts from each other and estimate them separately. The linear (linearized) part is estimated using the (extended) Kalman filter and the nonlinear part using the particle filter. The two estimates are then fused together using Bayes' rule.

The monitoring problem consists of online detection and isolation of components that for some reason has ceased to work properly. In an airborne application the requirement on system reliability is high. Therefore it is important to quickly detect and isolate a faulty component, e.g. if a failure in an accelerometer occurs. Methods for diagnosis with the particle filter must be developed.

5.3 Forward collision avoidance in cars

Jonas Jansson, Volvo, is developing a system for collision avoidance by active braking. The problem is how to use sensors as radar, accelerometers and gyros to decide when the driver can no longer avoid an accident and let a control algorithm brake the car to avoid or at least decrease the consequences of an accident.

5.4 Periodic versus event based sampling in signal processing

This project is carried out by Niclas Persson. Classical signal processing is based on periodic sampling. Event based sampling occurs when the time instants are collected, when the amplitude passes certain levels. Compared to integral theory, this might be called Riemann and Lebesgue sampling. The signal processing problem is to analyse or remove noise in both amplitude and time.

There are several identified applications. As one starting point, wheel velocity signals in cars are considered. The angular velocity of a wheel is measured at regular angular intervals in the ABS system, and are thus not synchronous in time. The event based sampling is disturbed by imperfections in the sensor's toothed wheel, while the amplitude disturbance is caused by vibrations in driveline, tires and surface. At least the tire vibration is not velocity dependent. This velocity signal is fundamental for all modern control and safety systems in cars.

Chapter 6

Detection and Diagnosis

6.1 Diagnosis in Discrete Event Dynamical Systems

With the growing complexity of todays engineering systems, the need has arisen for systematic approaches to failure diagnosis. We have previously proposed an approach for modeling and diagnosis of systems that fall in the area of discrete event dynamic systems. The approach is applicable to all systems that at some level of abstraction have an interesting discrete event dynamics that can display faulty behavior. The systems suitable for this approach typically consist of several interacting components where abrupt, but non-catastrophic, faults can occur in the components.

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

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

The diagnosis approach consists basically of three parts:

1. Modeling of the system to be diagnosed, by constructing a discrete event model containing both the normal and faulty behavior.

2. Fault detection and fault isolation using observations from the real system.

3. Analysis of diagnosability properties of the system.

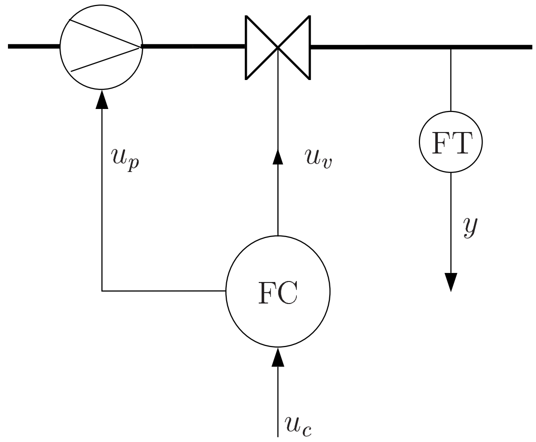


Figure 6.1: Flowchart of a simple system.

6.1.1 Modeling

Components are modeled locally in reusable component models including both normal and faulty behavior. Faults are modeled as fault states with unobservable transitions to them, that a component can chose non-deterministically at any time. The mapping from system variables to sensor readings can be obtained either globally and included in the relational model, or via local modeling.

To illustrate the methods and concepts, we consider a very simple example system that is shown in Figure 6.1. The system consists of a valve, a pump, a sensor that indicates presence or absence of flow, and a controller. In the figure, the controller is denoted FC (Flow Control) and the sensor is FT (Flow Transmission). The pump and the valve can be either on/off respectively open/closed. The valve and the pump can also fail in two different ways, stuck open or stuck closed, respectively stuck on, stuck off, see Figure 6.2 for a FSM model of the valve. The other variables indicated in Figure 6.1 will be Boolean valued, with the obvious interpretation. For example $u_v = 1$ means the valve is ordered open, etc.

The controller is designed to give flow by first opening the valve and then turn the pump on, and vice versa. See Figure 6.3.

The sensor measures if there is flow in the pipe. The condition for the sensor output y to be 1 is that both the pump and the valve enables flow.

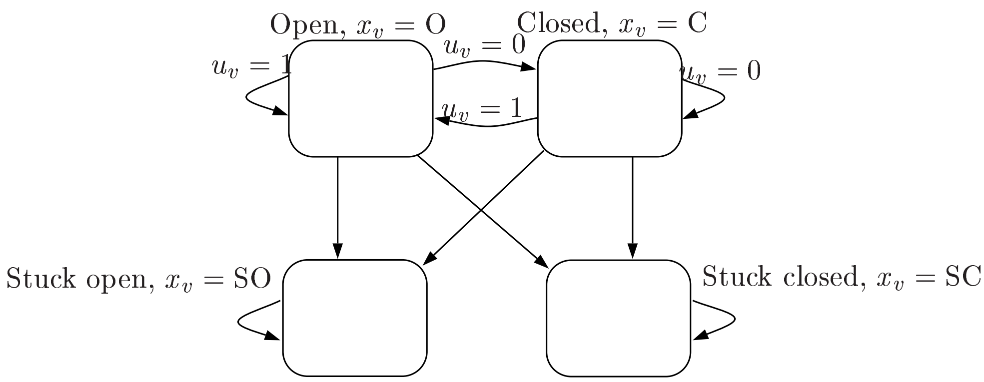


Figure 6.2: Valve component model with modeled faults, denoted $M_v(x_v, u_v, x_v^+)$.

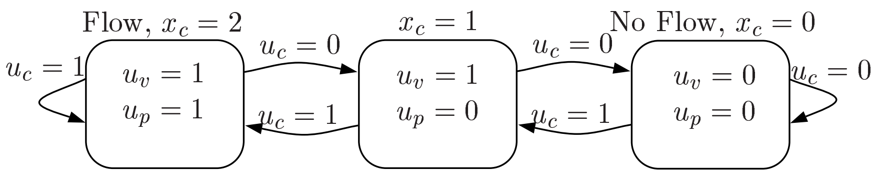


Figure 6.3: Controller for the valve/pump system, denoted $M_c(x_c, u_c, u_v, u_p, x_c^+)$.

This can be expressed as

$$y = \phi_v \wedge \phi_p$$

where

$$\phi_v(x_v) = (x_v == \mathrm{O} \vee x_v == \mathrm{SO})$$
$$\phi_p(x_p) = (x_p == \mathrm{On} \vee x_p == \mathrm{SOn}).$$

The global sensor relation is hence

$$S(x_v, x_p, y) = (y == (\phi_v \wedge \phi_p)).$$

The model of the system can then be obtained by

$$M(x, u_c, y, x^+) = \exists u_v, u_p.\ S \wedge M_v \wedge M_p \wedge M_c$$

where $x = \{x_v, x_p, x_c\}$. The now internal signals u_v and u_p are quantified to simplify the model, and it is done without losing any information since they are completely specified by the state of the controller.

6.1.2 Fault Detection and Isolation

The diagnosis problem is basically to infer the possible values of the unobservable fault inputs and states from observations of the system. Procedures for fault detection and fault isolation using the basic operations of the relational framework are presented in [23] and a simplified version of a spacecraft engine is studied in [55].

6.2 Fault Isolation in Control Systems with Object Oriented Architecture

6.2.1 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 Section 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. The problem is illustrated in Figure 6.4.

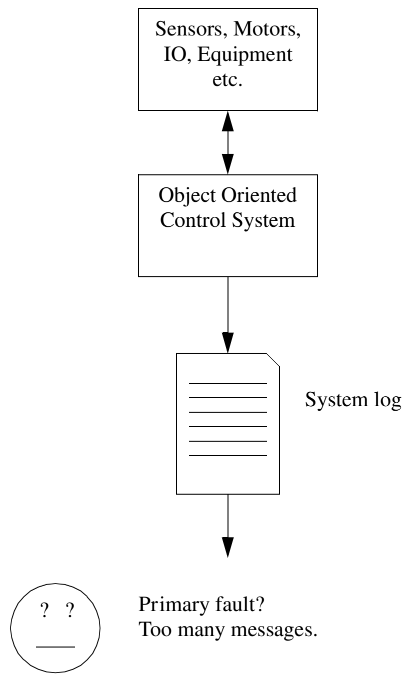


Figure 6.4: Problem overview

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. The scheme is illustrated from the operator's point of view in Figure 6.5.

A prototype implementation of the approach has been made and tested on the ABB Robotics industrial robot control system. A fault scenario from the ABB Robotics industrial robot control system is demonstrated in the next section. The approach is presented in in [23] [93].

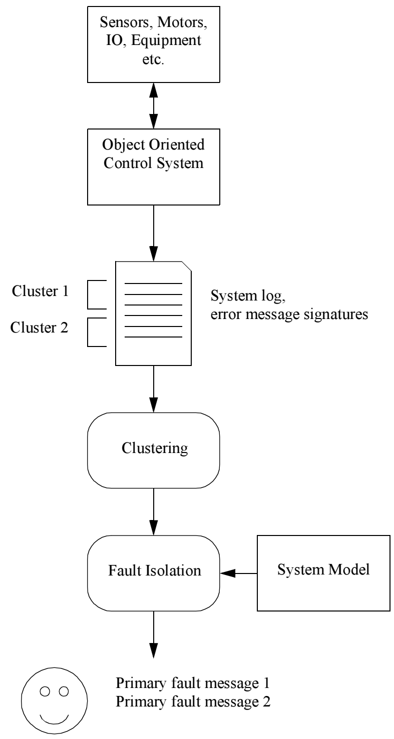


Figure 6.5: Main flow diagram of the fault isolation procedure

6.2.2 Example

We will briefly go through an example where the implemented fault isolation scheme is applied to a real fault scenario from the ABB Robotics industrial robot control system. We will follow the scheme outlined in Figure 6.5.

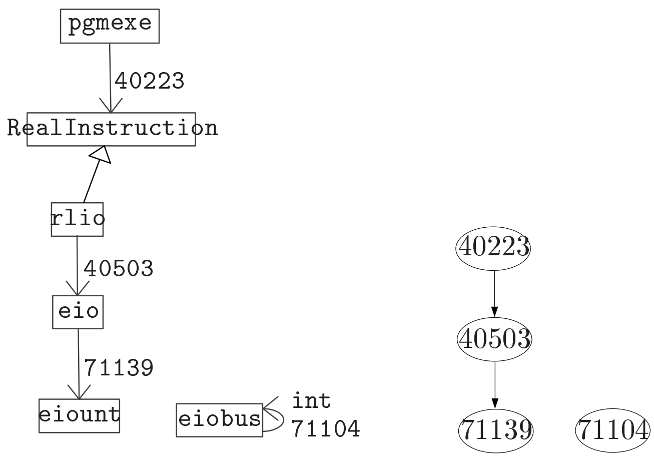
In the scenario, the robot is running a user-defined program, that involves IO-communication with external equipment via the built-in CAN-bus. The bus suffers a fault, that is reported to the message log. Some time later, the program needs to access the bus, which leads to a propagation of error conditions, causing several error messages from different parts of the system and finally an emergency stop. The relevant part of the message log is shown in Figure 6.6. In general, the message log contains in many messages that have no connection with the specific fault scenario at hand, and the relevant part of the log must be picked out. This is called *clustering* of the log.

```
All log messages
Date of saving: 19981120 15:42

1.  71104 Error on I/O Bus 0342 13:40.52
Description\Reason:
- An abnormal rate of errors on the
  BASE Bus has been detected.

2.  71139 Access error from IO 0342 13:41.7
Description\Reason:
- Cannot Read or Write signal s1 due to
  communication down.

3.  40503 Reference error 0342 13:41.7
Device descriptor is
not valid for a digital write operation

4.  40223 Execution error 0342 13:41.7
Task MAIN: Fatal runtime error

5.  10020 Execution error state 0342 13:41.7
The program execution has reached
a spontaneous error state

6.  10005 Program stopped 0342 13:41.7
The task MAIN has stopped. The reason is that
an external or internal stop has occurred.
```

Figure 6.6: The relevant part (cluster) of the message log for our fault scenario.

Even after clustering, the set of error messages can be hard to interpret without insight into the internals of the control system. In this case the most relevant message, informing us that the bus has failed, is the first in the cluster, but that is not necessarily true in general.

We formally represent a fault scenario with what we call a *base graph*, where the edges correspond to error messages, and the nodes correspond to objects, threads and packages in the run-time control system. The base graph corresponding to the message log in Figure 6.6 is automatically generated, and is shown in Figure 6.7(a). From the (initial) base graph in Figure 6.7(a), a cause-effect relation between the error messages can be derived by an automatic procedure. This cause-effect relation is represented by the graph in



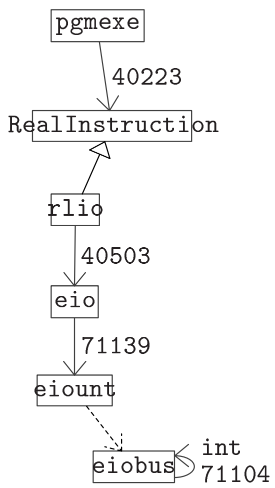
(a) Initial base graph. (b) Initial explanation graph.

Figure 6.7: The initial base graph and explanation graph for our fault scenario.

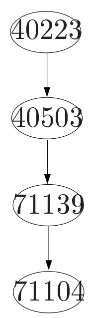
Figure 6.7(b), where the nodes are error messages.

As seen in Figure 6.7(b), the cause-effect relation constructed from the initial base graph does not contain a unique maximal element in this case. This of course depends on that the initial base graph is not connected; the chain of relational error messages does not have a direct connection to the error message stating that the bus has failed (71104). By using a structural *system model*, that contains the information that the class `eiount` depends on services provided by the class `eiobus`, we can *extend* the initial base graph as shown in Figure 6.8(a). The added (*derived*) edge in the base graph is shown dotted, to distinguish it from the edges corresponding to real error messages. The chain of propagating error messages can now be clearly seen, and the corresponding cause-effect relation shown in Figure 6.8(b) has a unique maximal element; the one stating that the CAN-bus has failed.

By using package information, i.e., a grouping of objects on a higher abstraction level, the dependence on the system model for base graph extensions can be decreased.



(a) Extended base graph.



(b) Explanation graph.

Figure 6.8: The extended base graph and corresponding explanation graph for our fault scenario.

6.3 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. The project consists of two subprojects; one (with ABB CRC) which considers the *general diagnosis problem*, and another (with ABB ASY) which considers the special problem of detecting *valve stiction*.

6.3.1 Fault detection and diagnosis in process control systems

A common problem within the process industry is that many control loops do not operate in a satisfactory way. Typical problems are, for instance, oscillations, sensor offsets and drifts, valve stiction etc. Since a typical plant consists of hundreds or thousands of control loops which interact in a rather complex way, it is very hard detect and classify such type of problems.

The long term goal is to develop a model-based diagnostics system. The idea is to utilize models of different sections of the process in question and that all available sensors in each sector are used for detecting and isolating faults. In general we are interested in:

- Sensor faults, e.g.,
  - drift
  - offsets
  - dead signals
- Actuator faults, e.g.,
  - offsets
  - erosion
- Data reconciliation, i.e., how to recover data if something goes wrong. This involves terms like *sensor fusion*.
- Instrumentation, i.e., determine what types of sensors we should use and where to put them.

The project has in particular focused on problems within pulp and paper applications. A simplified model of a part of a beater house has been defined and and has been used for generating data with simulated faults in sensors and actuators. The data have then been used for evaluating a number of fault detection schemes based upon both parameter estimation methods and kalman filtering techniques.

6.3.2 Detection of valve stiction

When a valve is used for controlling a flow in a pipe, a commonly encountered problem is that the valve sticks in certain positions, causing poor control performance. This is usually known as *stiction* or *stick-slip motion*.

A number of methods that diagnose stiction has been suggested in the literature. However, the methods require either detailed process knowledge or assume that the control loop oscillates in a certain way (which is not always the case). In this project we propose a model-based method that removes these requirements. It utilizes statistical criteria and matched filters and is inspired by tools and theory from the fields of *change detection* and *segmentation*. The work has resulted in one patent application.

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 applications currently under study include: control theory aspects of transmitter power control, algorithms for radio resource management, methods to improve analog-to-digital converters for radio receivers, an performance evaluation of control strategies for Internet traffic control.

7.2 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. Different aspects of power control are discussed in the PhD thesis [1].

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.

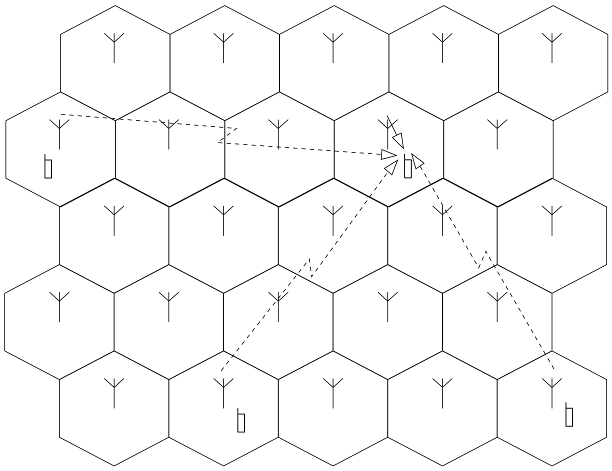


Figure 7.1: The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

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)

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

  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.

Using information feedback, the local distributed control loops are linear with good performance. Therefore, linear systems methods apply to analyze local stability and to design controllers [34]. With decision feedback, the local loops can be considered as linear except for relay feedback [35]. In both situations, the performance is essentially limited by time delays in the local control loops.

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 [1].

Below, some important aspects of power control are listed.

- 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 controller 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.

Performance is significantly degraded when subject to time delays in the distributed control loops. A compensation strategy is described in [34, 35], which essentially is based on the Smith predictor.

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

7.3 Radio Network Self-Configuring Systems

The rollout of third generation cellular radio systems is among other things characterized by more complex systems some less experienced operators running networks than before. Therefore, there is a need to provide intuitive means to operate the networks. Moreover, the sheer size of the future radio networks also calls for automatic parameter settings. For example, the number of configurable parameters in a GSM cell today is between 200 and 300. In addition, the networks of the third generation will be deployed faster than the systems of the second generation.

One approach is to separate the resource management in three layers:

1. Radio network algorithms. This layer consists of conventional, and to some extent standardized, radio network algorithms such as power control (see previous section), handover etc.

2. Adaptive radio network control. This layer coordinates the radio network algorithms. It provides adaption to varying conditions, such as changing traffic distributions or updated network configurations (for example new base stations).

3. Policy-based control. Different operators have different strategies when operating the systems. One may prioritize coverage and voice, and another real-time applications with guaranteed quality, but limited coverage, etc. The challenge is to provide an intuitive front-end to the operator.

From a control theory perspective, this is essentially three level cascade control, where outer control loops provide reference signals to inner, faster control loops.

The activities are concentrated to:

- Identification and modeling of the radio network, based on control theory methodology. Primarily, the algorithms will be separated with respect to time constants, input and output signals, and physical location, to identify potential conflicts.

- Development of coordinating radio network algorithms (level 2 above). This also includes studying cross-couplings and conflicts between existing algorithms.

- Disclose relevant and intuitive quantities for policy-based control.

Results on capacity and relative load, and modeling of power control algorithms are further explored in [1]. Current activities include three master theses. Fredrik Gunnarsson, Fredrik Gustafsson and Erik Geijer Lundin are working in this project.

7.4 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 ADC 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 AD converters with very high linearity to distinguish a weak signal from the harmonics from stronger signals.

7.4.1 Blind Equalization of Non-linear Distortion

To keep the power consumption and price at low levels, CMOS technology is a good option. One major problem is manufacturing errors leading to large uncertainties in the components. The AD converter consists of a resistance ladder, see Figure 7.2. The digital values are found by comparing the analog

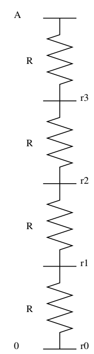


Figure 7.2: Errors in the resistances cause distortion in the digital signal.

signal with the voltages between the resistances. Errors in the resistances lead to non-linear distortion in the ADC. Here we have developed a patented method to adaptively and blindly compensate for the distortion with an algorithm suitable for implementation on the chip. The algorithm is described in [46]. We are currently evaluating the algorithm on measurements from a real AD converter.

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

One way to improve the speed of an ADC is to put several slow ones in parallel, whose outputs are then multiplexed to one signal of high bandwidth, Figure 7.3. Here it is of utmost importance to compensate for amplitude and timing (jitter) offsets, otherwise fake components in the frequency spectrum will appear. Here a patented adaptive algorithm has been developed.

Jonas Elbornsson and Fredrik Gustafsson are working in this project.

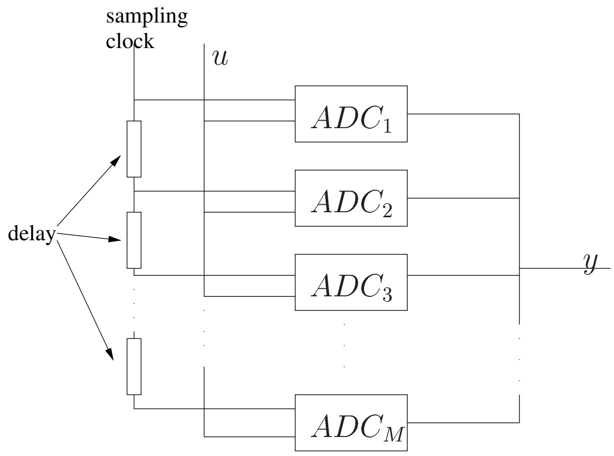


Figure 7.3: Parallel ADC structure, errors in the delay times cause distortion

7.5 Control, Fault Detection and Estimation in Data Networks

This is a recently started project, with focus on Internet traffic control. The core problem is that the standardized control implementations 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. Current work includes developing a simulation model of TCP/IP and apply different control and estimation algorithms for congestion control. Frida Gunnarsson, Fredrik Gunnarsson and Fredrik Gustafsson are working in this project.

Chapter 8

Robotic Applications

8.1 Introduction

This work is to a large extent carried out in cooperation with ABB Robotics within the competence center ISIS (Information Systems for Industrial Control and Supervision). The overall aim of the work is to study and develop methods for improvement of the performance of robot control systems. In [23] some further robot related work is presented, dealing with fault isolation in object oriented control system. This work is further presented in the Section Detection and Diagnosis.

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.

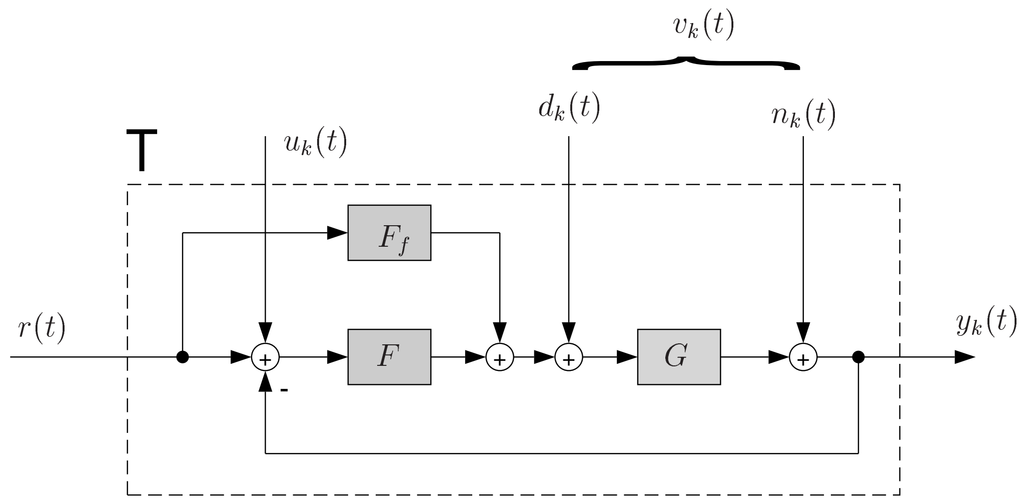


Figure 8.1: Control system

The work involves both theoretical studies and experimental evaluation of ILC algorithms and the results of both types were summarized in the PhD thesis [2]. Of particular theoretical interest is for example the study of so called second order ILC algorithm, where the correction signal $u_k(t)$ is formed using the error from the two previous iterations. Results from these studies, concerning e.g. convergence rates and design issues, are also presented in [26] and [49].

A standard assumption is that the behavior of the system to be controlled and the load disturbance $d_k(t)$ are repetitive. In situations where this is not the case the use of adaptive ILC can be motivated. In [2] and [56] design, analysis and experimental evaluation of an adaptive ILC algorithm is presented. The algorithm is derived using a state space description of the problem, and this enables the use of a Kalman state estimator for optimal handling of the disturbances.

Extensive experimental evaluation has been carried out using an ABB IRB1400 installed at the Division of Automatic Control. The evaluation concerns, as mentioned, second order and adaptive ILC algorithms, but also several “classical” ILC algorithms. Results from the experiments are presented in e.g. [2] and [24]. One of the existing ILC algorithms that has been evaluated is the algorithm obtained by minimizing a quadratic criterion in the control error and ILC input signal. For this type of ILC algorithm some theoretical aspects, involving for example a frequency domain interpretation, have been considered. Results from these studies are presented in [48].

In conventional industrial robots the variables of main interest are position and velocity of the tool. The variables available for measurement are however the joint angles only. In some situations the mechanical flexibility causes the tool position to differ from the position calculated using the joint angles. In such a case some extra information is needed in order apply ILC. In [25] some initial studies and simulations are presented for the case that an accelerometer measuring the tool acceleration is used.

The work on ILC has also resulted in a patent application, [47].

8.3 Robot Identification

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 [74] some initial 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.

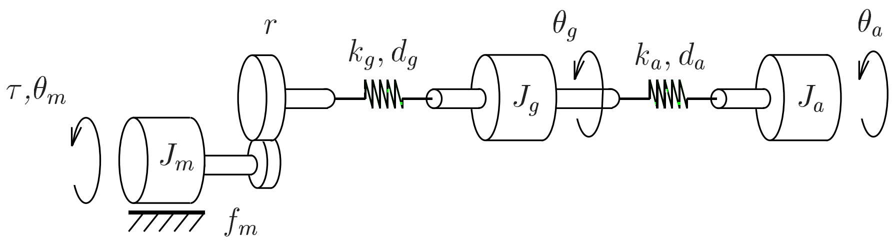


Figure 8.2: Three-mass flexible model.

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. In 1996 he was awarded an honorary doctor's s degree from the Baltic State Technical University in S:t Petersburg, Russia. In 1998 he as awarded an honorary doctor's degree from Uppsala University, Uppsala, Sweden.
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`

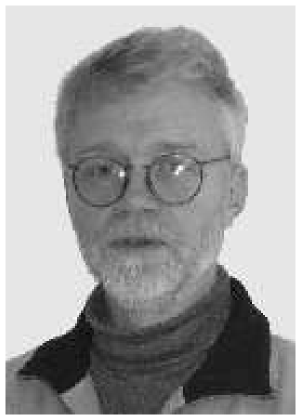
Mille Millnert is a Professor in the department. He was born in 1952 and received his M.Sc. in 1977 and his Ph.D. in Automatic Control 1982 from Linköping University. His research interests are Model Based Signal Processing, Parameter Estimation and the Combination of Numerical and Symbolical techniques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

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 Lecturer 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.
email: fredrik@isy.liu.se

Inger Klein is a lecturer 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.
email: inger@isy.liu.se

Tomas McKelvey was born in 1966. He received his M.Sc. degree in Electrical Engineering at Lund Institute of Technology in 1991 and his Lic.Eng. degree in 1994 and his Ph.D. in 1995 both at Linköping University. Since 1997 he is Lecturer at the department and his current research interests are in System Identification focusing on state-space models and subspace based methods both in the time and frequency domain.
`email: tomas@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 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. His current research interest is local polynomial modeling and its use in identification and control.
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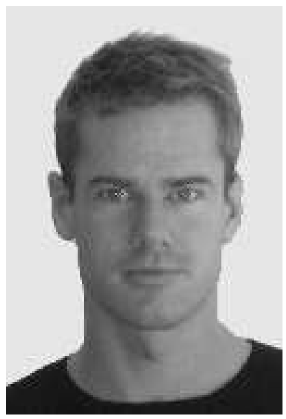
Magnus Larsson was born in 1970. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1995, his Lic.Eng. in 1997 and his Ph.D. in 1999 all at Linköping University. His current research interest is in the field of discrete event systems and diagnosis.
`email: magnusl@isy.liu.se`

Niclas Bergman was born in 1971. He received his M.Sc. degree in Applied Physics and Electrical Engineering from Linköping University in 1995, his Lic.Eng. in 1997 and his Ph.D. in 1999. His current research interests are nonlinear Bayesian filtering, terrain-aided navigation and tracking.
`email: niclas@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.
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Mikael Norrlöf was born in 1971. He received his M.Sc in Computer Science and Engineering 1996, his Lic.Eng. in 1998 and his Ph.D. in 2000, all at Linköping University. His current research interests include Iterative Learning Control as well as modeling, and identification of industrial robots.
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Valur Einarsson was born in 1970. He received his B.Sc. in Mechanical Engineering in 1994 from the University of Iceland and his M.Sc. in Applied Physics and Electrical Engineering in 1996, his Lic.Eng. in 1998 and his Ph.D in 2000, all at Linköping University. His current research interest is modeling and control of nonlinear systems.
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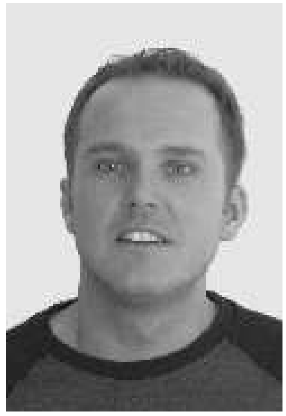

Fredrik Gunnarsson was born in 1971 He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 his Lic.Eng. in 1998 and his Ph.D in 2000, all at Linköping University. His current research interest is in the field of Radio Network Control.
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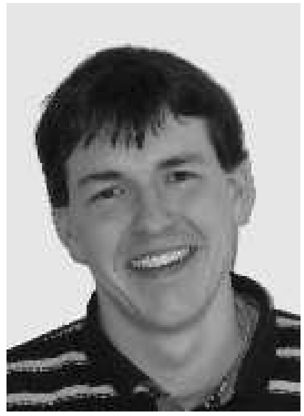
Fredrik Tjärnström was born in 1973. He received his M.Sc. Applied Physics and Electrical Engineering in 1997 and his Lic.Eng. in 2000 both at Linköping University. His research interests is uncertainty estimation of estimated models.
email:fredrikt@isy.liu.se



Ingela Lind was born in 1975. She received her M.Sc. in Applied Physics and Electrical Engineering in 1998 at Linköping University. Current research interest is regressor selection for on-linear black-box models.
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Johan Löfberg was born in 1974. He received his M.Sc. in Mechanical Engineering in 1997 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 from 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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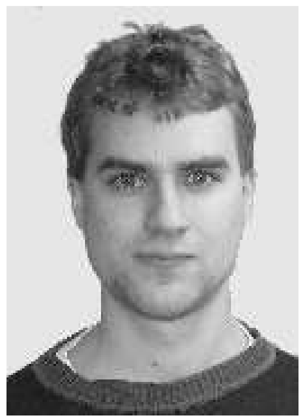

Jonas Elbornsson was born in 1975. He received his M.Sc. in Applied Physics and Electrical Engineering in 1998 at Linköping University.
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Jacob Roll was born in 1974. He received his M.Sc. in Applied Physics and Electrical Engineering in 1999 from Linköping University. His research interests ar ein 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.
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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.
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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.
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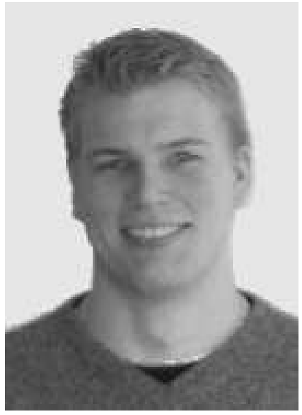

Frida Gunnarsson was born in 1977. She received her M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
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Martin Enqvist was born in 1976. He received his M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
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David Lindgren was born in 1968. He received his M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
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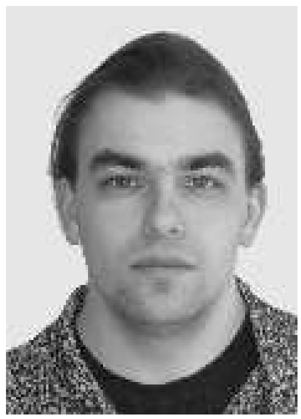
Wolfgang Reinelt Paderborn University, Paderborn, Germany was a post doctoral fellow from January 1999.
`email: wolle@isy.liu.se`

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



Joakim Svensèn, was born in 1977. He is employed as research engineer at the Division since December, where he is responsible for the laboratory equipment.
`email: joasv@isy.liu.se`

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

Dr. Liang-Liang Xie, Academia Sinica, Beijing, China was visiting postdoctoral fellow at the Division from September 1999 to September 2000.

Dietmar Bauer TU Vienna, Vienna, Austria was a post doctoral fellow from January 1 to July 1, 2000.

Alxander Poznyak CINVESTAV, Mexico, visisted the Division from mid January to mid April 2000.

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: Torkel Glad.

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

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

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

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Nonlinear systems, Signal processing. 30 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.

- *Modelling of Industrial Systems* (Modellering av Industriella System). For the Computer Science and Engineering and Industrial Engineering and Management Programs. Physical system modelling, Bond Graphs, Identification, Simulation. 15 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. Lecturers: Anders Stenman.

- *Real Time Process Control* (Realtidsprocesser och reglering). For the Information Technology Program. Real time systems. PID control. 25 participants. Lecturer: Anna Hagenblad.

- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, controllability, observability, feedback control. 25 participants. Lecturer: Anna Hagenblad.

- *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: Fredrik Gustafsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Avaliable for several Engineering Programs. 800 Participants. Lecturer: Niclas Bergman and Fredrik Gustafsson.

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, 40 participants. Contents: Sequential control and logic controllers. Fundamentals of automatic control, dynamical systems, feedback, differential equations, frequency analysis, Bode plots, stability, simple controllers, sampling, implementation, simulation of dynamic systems. Lecturer: Kent Hartman.

B.2 Graduate Courses

- *System Identification.* Lecturer: Lennart Ljung. Literature: L. Ljung, System Identification: Theory for the User. Prentice Hall 1999, 2nd ed

- *Dynamic Programming.* Lecturer: Participants of the course. Literature: D.P. Bertsekas, Dynamic Programming and optimal control, volume 1.

- *Linear Systems.* Lecturer: Torkel Glad. Literature: W. J. Rugh, Linear System Theory, Prentice Hall, 1996., T. Kailath: Linear Systems. Prentice Hall 1980.

- *Modelling.* Lecturer: 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 14 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 Sun Ultra 1
- 8 Sun Ultra 10
- 3 Sun SPARCstation 20
- 3 Sun SPARCstation 10
- 4 Sun SPARCstation 5

- 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
- 2 HP LaserJet 5 MPPostscript laser printer
- 1 Tektronix Phaser 350 solid ink-jet color printer

The Sun workstations run Solaris 2.6 and CDE (Common Desktop Environment). The software used in this network is mainly for advanced calculations and documenting. Among the mathematical programs are Matlab, Maple, Mathematica, 20sim, MATRIXx, Macsyma and Axiom. The system mainly used for preparing documents is TEXand LATEX. Accompanying programs such as xdvi, dvips and ghostview are also available. Write, Draw, Paint, Equation and Table from IslandGraphics, Inc., The Publisher from ArborText, Inc. and FrameMaker from Frame Corporation are other document handling packages that the network offers. The public services available (e.g. anonymous ftp areas, mail server and WWW) are described in Section 2 of this report.

The laptop computers are:

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

Appendix D

Seminars

- *Kort introduktion till grey-box-modellering* **Alf Isaksson**, Royal Institute of Technology, November 30, 2000
- *Does Bayes Rule?* **Stefan Arnborg**, Royal Institute of Technology, November 23, 2000
- *Basic Access Techniques in UMTS, Successor of GSM* **Krister Edström**, Ericsson Mobile Communications AB, November 23, 2000
- *MathModelica - a Tool for Physical Modeling, Simulation, Analysis, and Design* **Mats Jirstrand** MathCore AB, November 9. 2000
- *Design and Analysis of Adaptation Algorithms with Time-invariant Gains* **Mikael Sternad**, Uppsala University, October 26, 2000
- *ABBs nya multivariabel prediktionsregulator 3dMPC* **Mats Molander**, ABB, Ocotber 19, 2000
- *Syntetisk aperturradar (SAR)* **Sune Axelsson**, Saab AB, October 5, 2000
- *Robust controller design via linear programming* **Andrey Ghulchak**, Lund University, September 7, 2000
- *Analys av hybrida system* **Stefan Pettersson**, Chalmers University of Technology, May 24, 2000

- *Reglerteknik i traktionära drivsystem* **Henrik Mosskull**, Adtranz, May 18, 2000

- *MathModelica - A Full System Simulation Tool* **Johan Gunnarsson**, MathCore AB, May 4, 2000

- *On-line Identification and Adaptive Trajectory Tracking for Nonlinear Stochastic Continuous Time Systems Using Differential Neural Networks* **A. Poznyak**, CINVESTAN-IPN, Mexico, April 4, 2000

- *Parametric Methods for Nonlinear System Identification* **Sunil Kukreja**, McGill University, Montreal, Canada, April 5, 2000

- *Estimation and Control of Robotic Systems* **Xiaoming Hu**, Royal Institute of Technology, March 30, 2000

- *Asymptotic theory for the estimation of parametric nonlinear dynamic models* **D. Bauer**, University of Technology Vienna, March 23, 2000

- *Closed-loop identification with an unstable or nonminimum phase controller* **M. Gevers**, CESAME, Belgium, March 15, 2000

- *Model validation for robust control and controller validation: a prediction error approach* **M. Gevers**, CESAME, Belgium, March 14, 2000

- *Prediction and Planning in the WITAS UAV* **Patrik Haslum**, Dept. of Computer Science, Linköping University, March 2, 2000

- *Switching Structure State and Parameter Estimator for MIMO Nonlinear Robust Control with An Induction Motor Application* **A. Poznyak**, CINVESTAN-IPN, Mexico, February 17, 2000

- *Robust stochastic maximum principle* **A. Poznyak**, CINVESTAN-IPN, Mexico, January 27

- *Diagnostics and performance assessment for process industry controls* **K. Forsman**, ABB Automation Systems, January 24, 2000

Appendix E

Travel and Conferences

Svante Gunnarsson participated in Reglermöte Uppsala, June 6 - 8 and thte IFAC Symposium on Robot Control, Wien, Österrike, September 21-23.

Fredrik Gunnarsson participated in Reglertmöte 00 , June 6-8, and visited the Signals and Systems group June 5-6, both in Uppsala, Sweden. September 25-29, he participated in the IEEE Vehicular Technology Conference, Boston, MA, USA, and October 3, he visited the Wireless Information Network Laboratory, Rutgers University, NJ, USA. He took part in IEEE Global Telecommunications Conference, San Francisco, CA, USA, November 26 - December 1, and participated in the 6th Swedish CDMA Workshop, Thorskogs slott, Västerlanda, Sweden, December 7-8.

Anna Hagenblad participated in Reglertmöte 00 in Uppsala, Sweden in June in PBL-2000, Linköping in September, ERNSI, Vadstena September, CUP-dagen, Linköping, November, CDC, Sydney Australia December.

Magnus Larsson participated in the 4th IFAC Symposium On Fault Detection Supervision and Safety for Technical Processes (SAFEPROCESS 2000), Budapest, Hungary, June 14-16 2000.

Lennart Ljung visited ETH in Zürich and University of Stuttgart April 26-18. He gave a course on identification at the University of Siena, Italy, May 8 – 12, and visited Danfoss in Denmark on June 13. He participated in Regelrmötet in Uppsala June 6–8 and in the IFAC symposium on identification in Santa Barbara June 21 – 24, and took part in the ERNSI meeting in Vadstena Sept 25 -18. He was member of an evaluation commission that visited the Dept of Electrical Engineering of the ETH in Züric November 6 - 12, and he was in a thesis jury at UCL in Louvain-la-Neuve on November 14. He visited MIT in Cambridge, MA, November 27 – 30 and the Technical

University of Denmark in Lyngby on Dec 7.

Johan Löfberg participated in Reglertmöte 00 in Uppsala, ACC in Chicago, IL. USA and CDC in Sydney, Australia

Jonas Elbornsson paricpated in Reglermöte 2000, Uppsala June 6-8 and in the IEEE International ASIC/SOC Conference 2000, Arlington, Virginia USA 13-16 Sept.

Måns östring participated in "Qualitative Methods for Fault Diagnosis" Vacation School, July 10-12, 2000 in Terrassa, Barcelona, Spain.

Ola Härkegård participated in Reglermöte 00, in Uppsala and CDC, Sydney, Australien in December.

Per-Johan Nordlund participated in the Summer School on Signal Processing for Control, June 13-16, 2000, in Veldhoven, The Netherlands, Reglermöte 2000, June 7-8, 2000, in Uppsala, Sweden and the 39th IEEE Conference on Decision and Control, December 12-15, 2000, in Sydney, Australia.

Rickard Karlsson participated in CDC'2000 Sydney, Australia, Reglermöte 2000, Uppsala and the "Summer School on Signal Processing For Control, Dutch Institute of Systems and Control (DISC)" 13-16 June, Veldhoven, Nederländern

Dietmar Bauer visited Chalmers University of Technology, Göteborg, Sweden, Lund Univerity and the Royal Institute of Tecnology, Stockholm. He also participated in SYSIS, SAnta Barabara, CA, in June.

Mikael Norrlöf participated in Reglermöte 2000 in Uppsala, June 7 -8, in the IFAC Symposium on Robot Control in Vienna, Austria, September 21 - 23 and in the 39th IEEE Conference on Decision and Control, in Sydney Australia, December 12-15 and in

Ulla Salaneck participated in Reglermöte 2000 in Uppsala Sweden and in ERNSI 2000 in Vadstena, Sweden.

Appendix F

Lectures by the Staff

- Dietmar Bauer: *A survey on subspace methods*, Department of Electrical Engineering, Linköping University, February 4
- Dietmar Bauer: *Estimating linear dynamical systems using pseudo-maximum likelihood methods or subspace algorithms*, Department of Mathematics, Linköping University, February 23
- Dietmar Bauer: *Using $L)_p$ near epoch dependence for the derivation of asymptotic properties of least squares estimators*, Chalmers University of Technology, May 2
- Dietmar Bauer: *Analysis of the Larimore type of subspace methods* Lund University, Lund, May 19
- Dietmar Bauer: *A review on subpsace methods* May 29
- Dietmar Bauer: *On the impact of weighting matrices in subspace algorithms*, SYSID conference, Santa Barbara, June 21:
- Dietmar Bauer: *Optimal weighting for MOESP type of procedures* SYSID conference, Santa Barbara, CA, June 21
- Svante Gunnarsson: *Iterative Learning Control of a Flexible Mechanical System Using Accelerometers*. IFAC Symposium on Robot Control, Vienna, Austria, September 23

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- Johan Löfberg: Reglermötet Uppsala Poster presentation *Feasibility analysis of MPC with ellipsoidal terminal state constraints* Reglermöte 00, Uppsala, Sweden.

- Johan Löfberg: *Backstepping with local LQ performance and global approximation of quadratic performance* ACC, Chicago, IL, USA

- Johan Löfberg: *A stabilizing MPC algorithm using performance bounds from saturated linear feedback*,Conference on Decision and Control (CDC'00), December 12-15, Sydney, Australia

- Per-Johan Nordlund: *Synthetic attitude and heading reference for Saab Gripen* Conference on Decision and Control (CDC'00), December 12-15, Sydney Australia.

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- Mikael Norrlöf: *A model based Iterative Learning Control method applied to 3 axes of a commercial industrial robot* IFAC symposium on robot control, Vienna, Austria, September 21-23

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Appendix G

Publications

Ph.D. Theses

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Appendix H

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Appendix I

Master Theses (Examensarbeten)

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