LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
1999

Contents

Chapter 1

Introduction

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

Our research interests are focused on the following areas:

- *Nonlinear Modeling and Control*: Here we are interested both in developing theory for nonlinear systems and to understand and utilize how modern computer algebraic tools can be used for practical analysis and design.

- *System Identification and Signal Processing*: We are interested in a number of aspects ranging from applications of modern signal processing techniques, to theoretical aspects in how to evaluate model quality in the presence of under-modeling.

- *Hybrid Modeling*: This is an important and emerging field covering problems of how to deal with systems with both discrete and continuous phenomena. The modeling of discrete event dynamic systems (DEDS), sequential planning control problems, and various supervision and diagnosis problems also belong to this area.

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

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

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

During the year Urban Forssell, Niclas Bergman, Anders Stenman, Krister Edström and Magnus Larsson defended their Ph.D.-theses and Anna Hagenblad defended her Lic. Eng. degree.

In the following pages the main research results obtained during 1999 are summarized. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge, most easily from our web-site.

We invite you to visit our home page:

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

The competence center ISIS has the home page

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

and for the research school ECSEL turn to

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

Chapter 2

Network Services

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

We also have a generic email address:

`Automatic.Control@isy.liu.se`

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

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

2.1 World Wide Web

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

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

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

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

`mattiaso@isy.liu.se`

2.2 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.

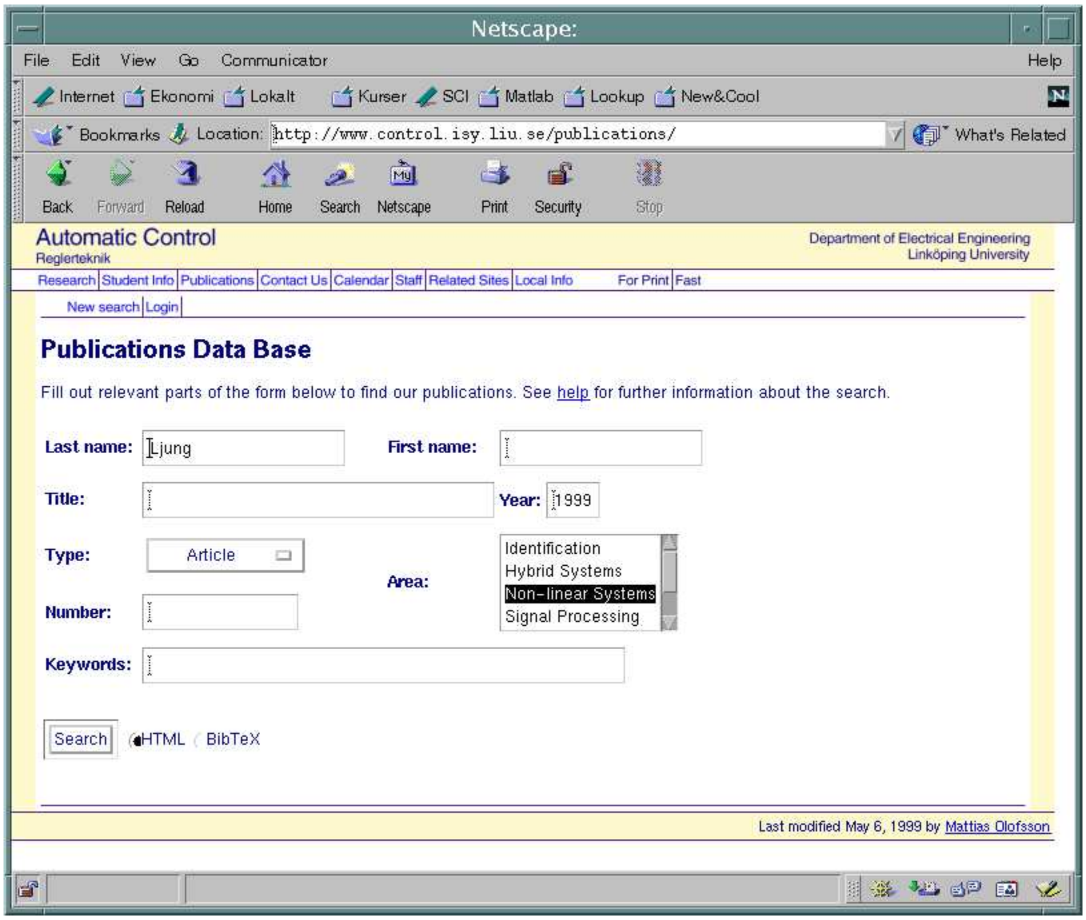


Figure 2.1: The publications data base interface

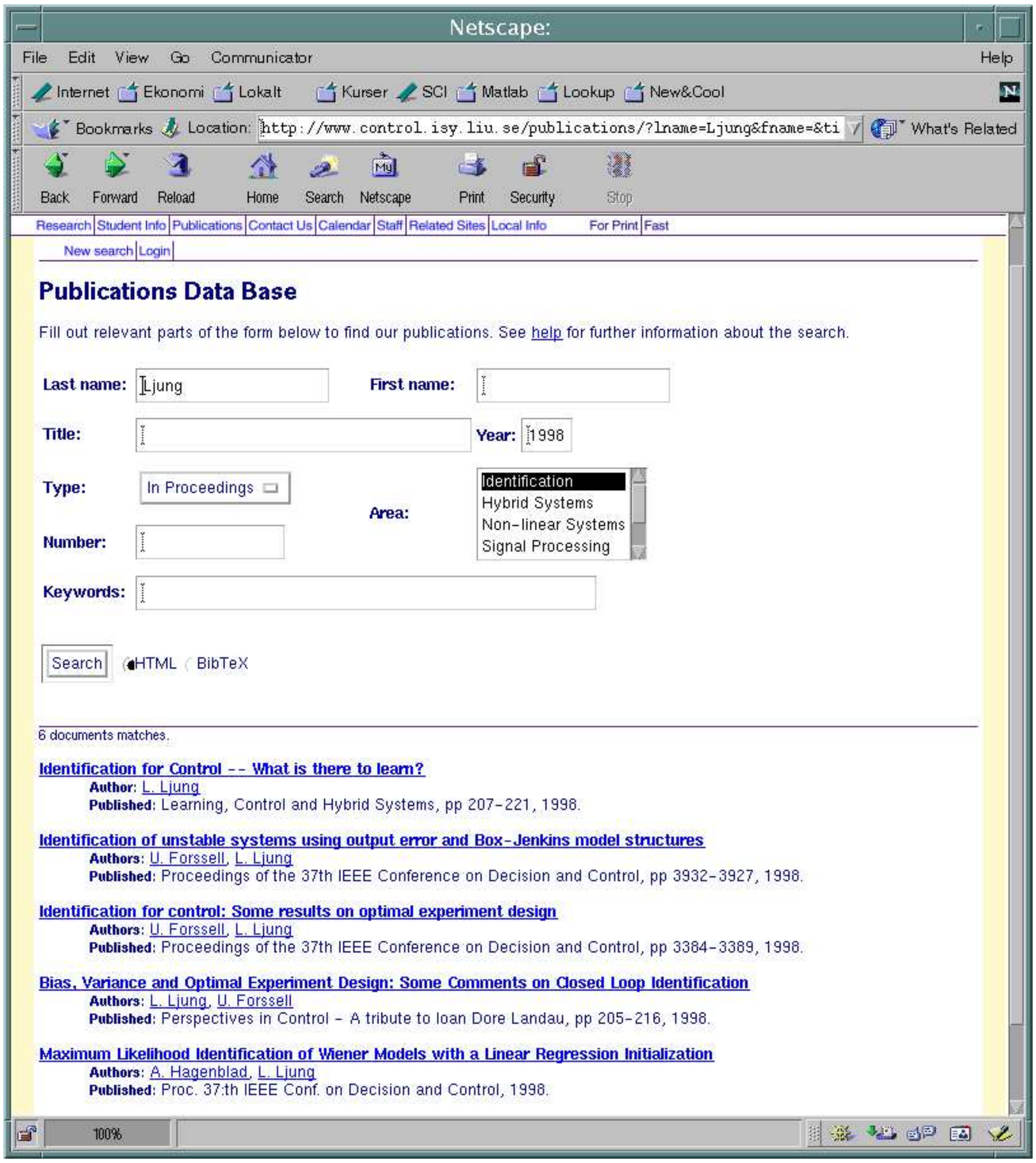


Figure 2.2: Example of search result

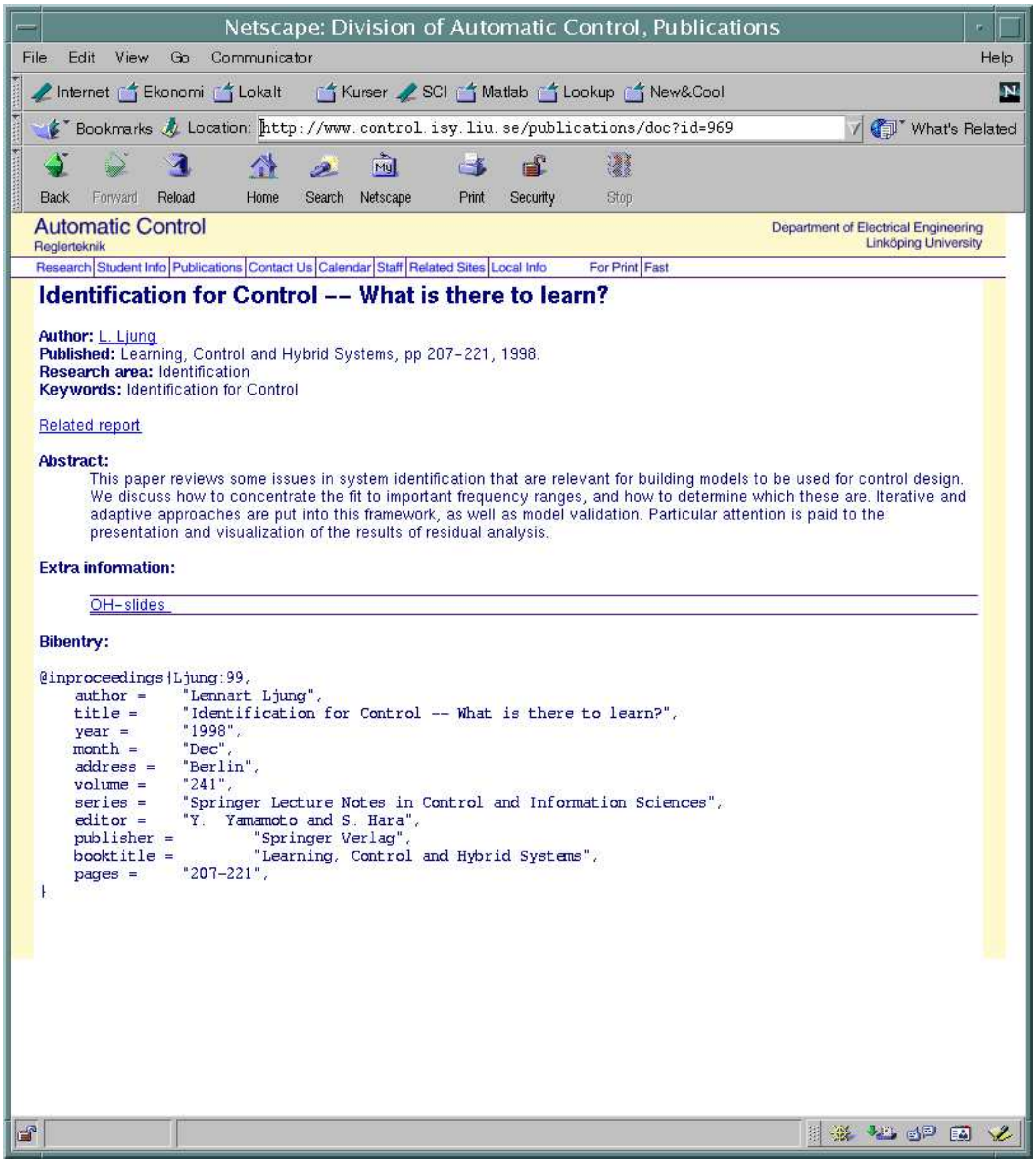


Figure 2.3: Example of a publication home page

Chapter 3

System Identification

3.1 Introduction

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

During 1999 two PhD theses were completed in the area: By Urban Forssell, [1], and by Anders Stenman, [2]. These will be further described in Sections 3.4 and 3.5, respectively.

Also, the licentiate thesis by Anna Hagenblad, [6], was finished. This will be discussed in Section 3.3.

3.2 State-Space Parameterizations and Efficient Numerical Techniques

Linear systems can be conveniently represented as state-space models. Model structures based on the state-space form can also be used for system identification, e.g. for prediction error minimization using a parameterized state-space model. Different state-space parameterizations are discussed in [44] with an emphasis on numerical properties and convergence speed.

Tre transformation of a MIMO system from state space form to input-output forms of ARMAX character is well defined but somewhat complicated. To trace the uncertainty of the parameters associated with the state-space form to those of the ARMAX forms may require a substantial amount of calculations. A fast and efficient algorithm for performing these computations is developed in [33].

3.3 Identification of Wiener models

A Wiener model consists of a linear dynamic system in series with 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.

Using a parametric description of the linear and nonlinear subsystems, a prediction error criterion can be used to estimate the parameters of the Wiener model. The criterion is often too complicated to allow an analytical solution of the problem, but it can be minimized numerically by, e.g., a Gauss-Newton method. Starting with an initial estimate, the numerical search can be designed to guarantee convergence to a local minima of the criterion, but there are often several local minima. It is thus important to find a good initial estimate. That local minima exist and may cause problems was investigated in [6].

Assuming the nonlinearity is invertible and parameterizing the inverse with parameters that enter linearly, it is possible to formulate a prediction error criterion where the parameters can be found by linear regression. In [6] and [22] this is used to get an initial estimate, which is then used in the numerical minimization of the original prediction error criterion. The method is applied to some test systems where it is found to work well, and also to experimental data from a distillation column.

3.4 Closed-loop Identification

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

It turns out that some 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 1999 we have studied some different aspects of the closed-loop identification problem. This has resulted in the PhD thesis [1] and a number of articles, [7, 8, 9, 10, 14]

The focus is on analyzing and devising prediction error methods for closed-loop identification. The perspective paper [10] summarizes most of our efforts in this area.

For the identifiability and bias distribution, the following expressions are the key tools: Let the true system be given by

$$y(t) = G_0(q)u(t) + H_0(q)e(t)$$

where e is white noise with covariance matrix Λ_0. Let the model structure be given by

$$y(t) = G_\theta(q)u(t) + H_\theta(q)e_\theta(t)$$

where e_θ is assumed to be white noise with covariance matrix Λ. Then the estimate $\hat{\theta}_N$ that minimizes the prediction error criterion will converge to

$$\arg\min_{\theta\in D_{\mathcal{M}}} \int_{-\pi}^{\pi} \mathrm{tr}\left[\Lambda^{-1}H_\theta^{-1}\begin{bmatrix}(G_0-G_\theta)^*\\(H_0-H_\theta)^*\end{bmatrix}^* \Phi_{\chi_0}\begin{bmatrix}(G_0-G_\theta)^*\\(H_0-H_\theta)^*\end{bmatrix} H_\theta^{-*}\right] d\omega$$

Here

$$\Phi_{\chi_0} = \begin{bmatrix}\Phi_u & \Phi_{ue}\\ \Phi_{eu} & \Lambda_0\end{bmatrix}$$

is the spectrum matrix for

$$\chi_0(t) = \begin{bmatrix}u(t)\\ e(t)\end{bmatrix}$$

It has the following useful factorization:

$$\Phi_{\chi_0} = \begin{bmatrix} I & \Phi_{ue}\Lambda_0^{-1} \\ 0 & I \end{bmatrix} \begin{bmatrix} \Phi_u^r & 0 \\ 0 & \Lambda_0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \Lambda_0^{-1}\Phi_{eu} & I \end{bmatrix}$$

where Φ_u^r is the spectrum matrix of that part of u that cannot be estimated, by linear time invariant filtering, from e. (If the input is obtained by linear feedback from the output with an added reference signal r, it is the spectrum of that part of u that originates from r.)

Another question we have studied is that of optimal experiment design, especially directed towards control applications. The papers [14] contains the core results here. Other topics covered include direct identification of unstable systems using output error and Box-Jenkins models [9].

A projection method for closed loop identification is outlined in [8].

3.5 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. The PhD thesis [2] summarizes most of the results.

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 [2] two algorithms corresponding to these approaches are presented and their asymptotic properties are analyzed. It is concluded that the optimization approach might produce more accurate predictions, but that it at the same time is more demanding in terms of computational efforts.

Compared to global methods, an advantage with the model-on-demand concept is that the models are optimized locally, which might decrease the modeling error. A potential drawback is the computational complexity, both since it is required to search for neighborhoods in a multidimensional regressor space, and since the derived estimators are rather demanding in terms of computational resources.

Three principal applications for the approach have been studied. The first one addresses the problem of nonlinear time-domain identification. In [2] a number of nonlinear model structures are evaluated from a model-on-demand perspective. It is shown through simulations that the prediction errors are in order of magnitude directly comparable to (or even better than) more established modeling tools such as artificial neural nets or semi-physical modeling. This conclusion is also supported by the papers [27] and [46].

The second application addresses the frequency-domain identification problems that occur when estimating spectra of time series or frequency responses of linear systems. In [2], [25] and [107] 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.

The third application, which is closely related to the first one, is control of nonlinear processes. Here we utilize the predictive power of the model-on-demand estimator for on-line optimization of control actions. In [45] a particular method, *model-free predictive control*, is presented, that combines model-on-demand estimation with established model predictive control techniques.

3.6 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 $x_1, \ldots, x_N$ 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 [26], 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, which is discussed in [77].

3.7 Model Validation and Model Error Models

The validation of an identified model is a crucial step in 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. In [75] it is discussed how such validation techniques relate to set membership identification.

In [58] a broader perspective of residual analysis is taken: Let us build an explicit model

$$\varepsilon(t) = G_{MEM}(q)u(t)$$

of how the input affects the residuals. This model could be of arbitrary nature, not necessarily linear. We call it the *Model Error Model*. The next step is to estimate the “size” of this model. In the linear case it can be well illustrated in the frequency domain. See Figure 3.1.

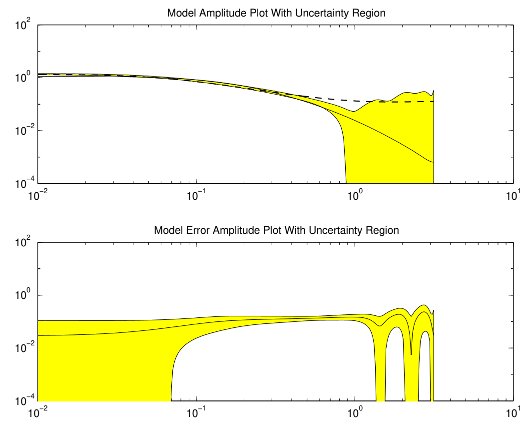


Figure 3.1: Upper plot: Nominal second order ARX model (dashed line) as well as nominal model + model error model with uncertainty region. The true system is marked with a solid line. (The nominal model plus model error model is not marked as a separate curve; just the corresponding uncertainty region.) Lower plot: The model error model (20th order FIR model) and its uncertainty region.

In [40] this view of the model error is compared with Goodwin’s stochastic embedding and with set membership identification.

3.8 Aspects on Identification Methods

Identifiability

Identifiability of models can be approached in several different ways. We have earlier shown how differential algebra and Ritt’s algorithm can be used to treat global identifiability. These results have been extended in [38] and [39] to deal with problems in connection with identification of combustion engines.

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 [104]. It is shown that this may lead to much improved efficiency, and also to better structure decisions, than estimating all the possible structure combinations.

Estimation Focus

The paper [34] discusses a facility to shift the estimation focus between 'Prediction', 'Simulation', or any SISO filter. With 'Prediction', a standard prediction error method is obtained. 'Simulation' means that the transfer function from input to output is computed as an Output Error model, while the noise model is estimated by a prediction error criterion, fixing the dynamics to the earlier estimated transfer function. The effects can be illustrated by the following sequency of MATLAB commands:

```
>> load iddata1
>> m1 = arx(z1(1:150),[2 2 1],'Foc','Pre');
>> m2 = arx(z1(1:150),[2 2 1],'Foc','Sim');
>> compare(z1(151:300),m1,m2)
```

This generates Figure 3.2.

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 [13] 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

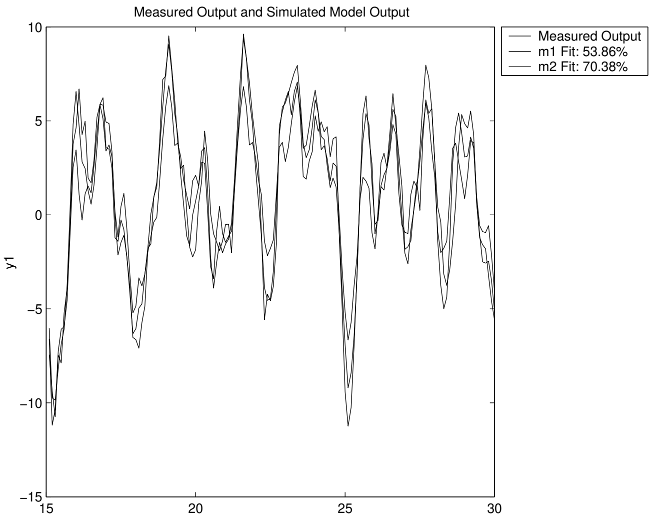


Figure 3.2: The simulated responses of model m1 (focus = prediction) and m2 (focus = simulation). m1 has a fit of 53% while m2 has a fit of 70%. The fit is the percentage of the output variation that is reproduced by the model.

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 [101] and [35]. The somewhat surprising result is that using L_2 model reduction it could in some cases be strictly better to estimate the low order model using reduction techniques, and in most cases we get the same variance as the direct estimation would have given.

Chapter 4

Nonlinear Systems

4.1 Constraints and Structures in Dynamic Systems

Extension of RGA to nonlinear systems

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

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

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

For a static nonlinear system

$$y = H(u)$$

it is proposed in [31] 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.

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 [89] 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 $\theta > 0$.

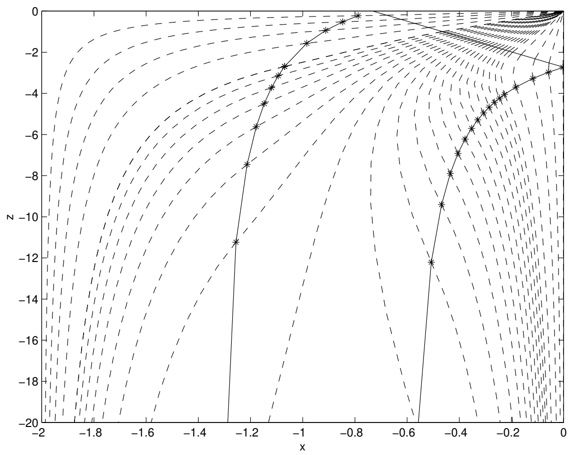
These concepts can be applied to the analysis of identifiability of internal combustion engines. In [39] some general ideas on this subject are presented. In [38] the identifiability of different parts of a car engine model are discussed. In particular the effect of adding or removing sensors and of varying a priori information is investigated.

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. An analysis of this situation is done in [90]. 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.

Other examples of constrained linear quadratic control were given in [92].

Response time limitations

One effect of control constraints is that the response time of a system can not be arbitrarily fast. For a linear system the response time is described by the rise time or settling time of a step response. A more precise measure is the minimum time required for transfer from the origin to the new equilibrium defined by the step. In [91] a lower bound for the minimum time is derived. Consider a linear system $G(s)$ whose input is constrained by

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

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

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

where τ is the largest time constant of the system.

Algebraic Methods in Control

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

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

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

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

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

4.2 Equilibria and Oscillations

Equilibria

Equilibria of a nonlinear system

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

are given by the equation

$$f(x, u) = 0 \tag{4.1}$$

The solutions form a set in x-u-space. In many applications one wants to move between different equilibria. It is possible to move between equilibria that can be connected by a curve of exponentially stabilizable equilibria. Moreover the transfer can be accomplished by staying arbitrarily close to equilibrium. In more complicated situations it might be necessary to switch control discontinuously because the set of equilibria is not connected. Such a case is shown in figure 4.1. The system dynamics is given by

$$\dot{x} = (u^2 + 4u - x + 3)(u^2 - 4u + x + 3)(x - u). \tag{4.2}$$

Oscillations and Diffusive Coupling

The identical systems

$$\dot{x}_j = f(x_j) + Bu_j, \quad y_j = Cx_j$$

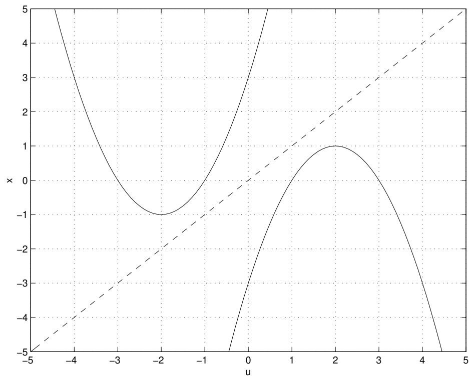


Figure 4.1: Equilibrium points of (4.2). Solid lines: asymptotically stable linearizations, dashed lines: unstable linearizations.

are said to be diffusively coupled if CB is similar to a positive definite matrix and if

$$u_j = -\gamma_{j1}(y_j - y_1) - \gamma_{j2}(y_j - y_2) - \ldots - \gamma_{jk}(y_j - y_k)$$

with $\gamma_{ij} = \gamma_{ji} \geq 0$ such that $\sum_{j=1}^{k} \gamma_{ji} > 0$ for all $i = 1, \ldots, k$. In chemical and biological systems diffusion is usually a smoothing-out process. However, in some cases it can lead to oscillatory behavior, although each system is globally asymptotically stable by itself. In [12] the conditions for this phenomenon are investigated. It is shown that instability of the zero dynamics of individual subsystems plays a crucial role. An example is provided by the two coupled systems

$$\begin{aligned}
\dot{x}_1 &= Ax_1(1 + |x_1|^2) + \gamma BC(x_2 - x_1) \\
\dot{x}_2 &= Ax_2(1 + |x_2|^2) + \gamma BC(x_1 - x_2)
\end{aligned}$$

where A, B and C are given by

$$A = \begin{bmatrix} 1 & -1 & 1 \\ 1 & 0 & 0 \\ -4 & 2 & -3 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

The transfer functions of the subsystem linearizations are

$$\frac{s^2 - s + 1}{s^3 + 2s^2 + 2s + 1}$$

showing the existence of right half plane zeros. If the coupling parameter γ exceeds the threshold value 0.6512 the diffusively coupled system becomes oscillatory. In figures 4.2 and 4.3 below the system behavior for γ-values below and above the threshold are shown.

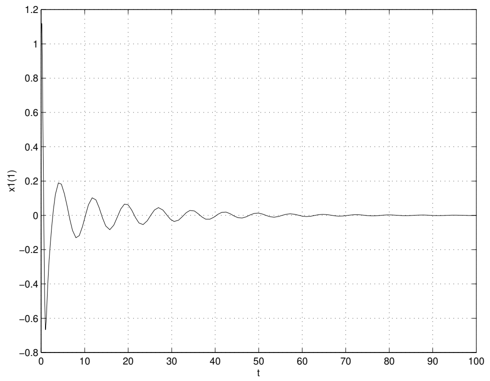


Figure 4.2: Response of system with weak diffusive coupling.

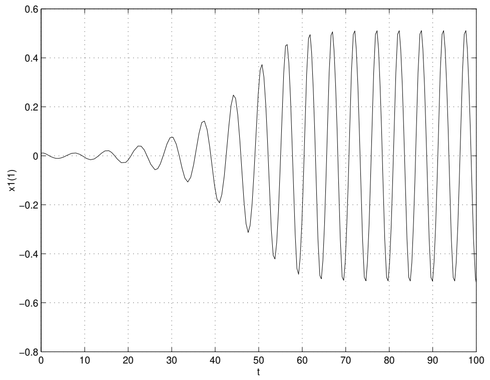


Figure 4.3: Response of system with strong diffusive coupling.

4.3 Nonlinear Design methods

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 in [41]. 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.

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 4.4

In order to analyze such a system we can approach the problem using Lyapunov functions [42] and integral quadratic constraints (IQC) [43]. The methods have been applied on two examples, both giving very similar stability bounds.

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

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).

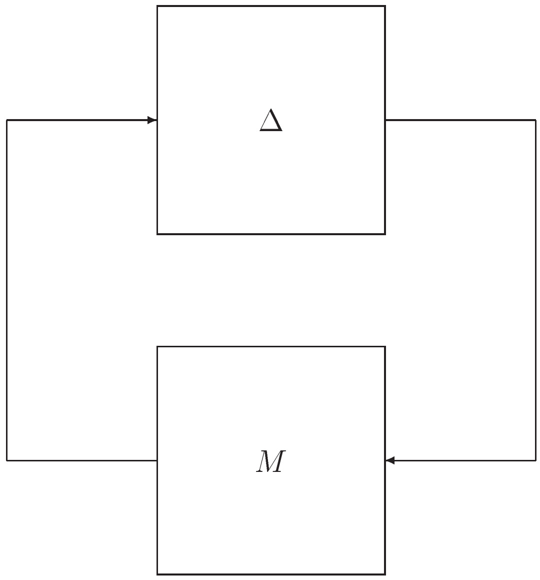


Figure 4.4: System with slowly varying uncertainties. The Δ block is assumed to be parameter dependent, while M is a linear time-invariant system. We assume that both Δ and its derivative, $\dot{\Delta}$, are bounded.

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. In [48] backstepping is used together with optimal control techniques, in particular techniques for inverse optimality. Applications to aircraft control are considered in [57]. It is shown that the aircraft dynamics after some approximations, can be written in the form required for backstepping.

Design Methods for Internal Combustion Engines

In [15] the stability of cascaded non-autonomous non-linear systems is investigated. In particular, the following questions are answered: (i) What happens with the solutions of a time-varying non-linear system which is globally uniformly stable (GUS), when it is perturbed by the output of a globally exponentially stable (GES) system, in particular, when both systems form a cascade? (ii) If a time-varying non-linear system is globally uniformly asymptotically stable (GUAS), is this stability properly presented when it is perturbed by an exponentially decaying input? The proofs are based on a standard 'delta-epsilon' Lyapunov analysis. The results are applied to the problem of stabilization of a turbo-charged diesel engine. In [62] the problem of model structuring to achieve robust design is studied.

Chapter 5

Signal processing

The group's activity in the signal processing field is reported in this chapter. Main event of the year is the doctoral thesis [3] about numerical and statistical methods for navigation.

5.1 Navigation Using Terrain Elevation Databases

The following is a brief summary of the thesis [3]. A related publication in Control system magazine is [11].

Consider the problem of aircraft navigation utilizing terrain information, presented in Figure 5.1. A radar altimeter measures the aircrafts ground clearance and a barometric altimeter measures the altitude over mean sea-level, their difference equals the terrain elevation. A database map with pre-measured values of the terrain elevation is carried on board the aircraft and used to filter out matching terrain elevation profiles, yielding a position estimate of the aircraft.

The problem admits a nonlinear state space model

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

where x_t is the two dimensional position of the aircraft in the map, u_t is the estimated movement of the aircraft obtained from an inertial navigation system, y_t is the measured terrain elevation, $h(\cdot)$ is the terrain map and v_t

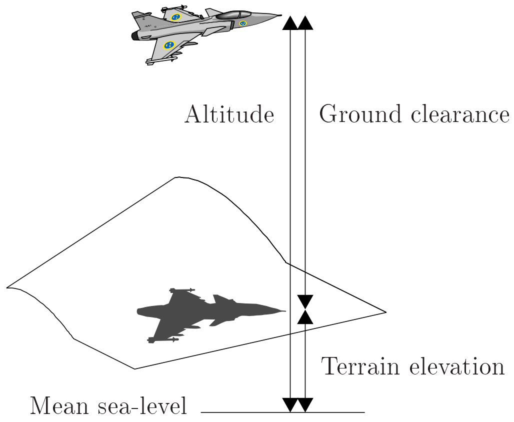


Figure 5.1: Terrain aided navigation.

and e_t are noises acting on the system. The unstructured information in the terrain makes the problem very hard to solve using standard algorithms for state estimation. The general Bayesian solution to the estimation problem consists of recursively updating the conditional filter density $p(x_t \mid Y_t)$. With some independence assumptions on the noises, the filter density obeys the recursion

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

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

Since approximative solutions are inevitable in the application fundamental lower bounds on the performance of the algorithm have been derived and compared with the implementation using extensive simulations. It is shown that the algorithm will reach the bound when the discretization distance is chosen small enough [3].

5.2 Sensor Fusion

Sensor fusion deals with the problem of extracting information about objects and their environment by combining observations from several different sensors. The terrain-aided navigation application described in Section 5.1 is one example of a sensor fusion problem. The comparison between the map and the measurements constitute a nonlinear estimation problem where unconventional and conceptually different sources of information are fused together with the objective to determine the aircraft position.

The work in this area has been focused on the issue of on-line state estimation for applications that are described by nonlinear and non-Gaussian state space models. Algorithms for simulation based recursive estimation have been studied. Future research will involve further development of particle filters for optimal Bayesian inference in recursive estimation. These techniques will be applied to state of the art integrated navigation systems in cooperation with fault detection and isolation algorithms. The particle filters are also being applied to the problem of tracking several agile targets in the presence of false target detections. Both navigation and tracking applications involve highly nonlinear models and therefore constitute challenging application fields were the application and development of particle filters and MCMC techniques will prove fruitful.

During the fall of 1999, four PhD students started who all with work with sensor fusion. They also have in common that they are partially employed by industry: SAAB Aircraft, SAAB Dynamics, Volvo Car and NIRA Automotive, respectively. In the same order as above, the projects are

- aircraft navigation, filter evaluation and fault detection using MCMC methods,
- aircraft target tracking and identification using MCMC methods,
- automotive collision avoidance including radar measurements,
- automotive state estimation including tire pressure, motion state and friction.

These projects will most probably overlap and interact in a quite constructive way. Common denominators include motion models, Kalman filters, gyro measurements, sensor fusion, filter design/evaluation and fault detection with diagnosis.

5.3 Target tracking

As an application particle filter and MCMC framework in the previous section, we applied the ideas to target tracking problems in [32]. In previous work, we have compared extended Kalman filter and variants of filter banks including the IMM algorithm. In [32], we repeated the same case study with Markov Chain Monte Carlo (MCMC) methods and we were thus able to compare the pros and cons of these rather different approaches.

5.4 Blind equalization

A combinatorical approach to blind equalization was reported in [16]. The well-studied probem is to estimate a model for the channel distortion and the transmitted input sequence at the same time, only using the received output sequence and the finiteness of the input alphabet. The idea is that the final input alphabet together with a finite impulse response channel distortion give rise to certain clusters in the observed outputs. The transition from one cluster to another gives much information about possible input sequences. In particular, it is shown that the same transition pattern is observed twice, then the input sequence is identifiable. The result is fundamental in that it does not depend on the actual algorithm that is applied.

Chapter 6

Hybrid and Discrete Systems

6.1 Physical Modeling and Simulation of Hybrid Systems

Physical Modeling

The reason why the term *physical modeling* has been coined is the need to distinguish between two extreme approaches to physical systems modeling. On the one extreme we have so called 'black-box modeling' where a mathematical model is fitted to measurements. On the other extreme we have physical modeling in which case we only use insight into the system structure combined with known physical laws to derive an appropriate mathematical model.

In practice though, none of the two extreme approaches are particularly fruitful in isolation. In order to model any non-trivial system, the two approaches will have to be combined. However, depending on the character of the system, one of the two modeling activities, i.e., physical modeling or parameter estimation, may dominate the overall modeling effort. In this section we focus on the physical modeling process.

The General Approach

The classical engineering approach to physical (systems) modeling is best characterized as a three phase modeling paradigm. First, we have the *reticulation*, where the system is divided into, and described by, *physical mecha-*

nisms and their interactions.

The second phase consists of a *mathematical characterization* where the mathematical relations characterizing the physical mechanisms are specified. These relations are typically referred to as *constitutive relations*. By proper definition of the physical mechanisms used in the first phase, this step can partly be automated. This second phase constitutes a second step of abstraction away from the actual system.

In the third phase we *compile* the above relations into a suitable computational form, that can be used for both formal model analysis and simulation.

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

The primitive bond graph elements have well-defined physical and mathematical semantics. Therefore the second phase is often trivial, and can in many cases even be automated. Finally, the derivation of, e.g., differential and algebraic systems of equations (DAE systems) from a characterized bond graph is straightforward.

Hybrid Systems

Abrupt changes in the dynamic behavior of physical systems are common in engineering applications. In fact, many engineering devices are designed intentionally to obtain near ideal switching behavior, e.g., electric relays, diodes, mechanical clutches, free wheeling devices, hydraulic valves, hydraulic check valves and so on.

By using the previously introduced **Sw**-element, when making bond graph models, the support from bond graph formalism is extended to hybrid systems, [4]. Bond graphs using the **Sw**-element are referred to as switched bond graphs.

Equation Generation and Simulation

It is straightforward to generate a mathematical model from a switched bond graph. The procedure includes generation of a finite automaton describing the relations between the different modes as well as finding a continuous model for each mode. These continuous models can be derived using standard causality propagation and equation generation rules. In addition some rules for initializing the continuous states in a mode have to be derived to complete the mathematical description. Since the states in most cases are continuous, the initialization is often trivial. In non-trivial cases the initial values can be found as solutions to equations generated from the bond graph [4, 20]. The generation of the equations is algorithmic, and common bond graph equation generation algorithms can be used. The algorithms have also been verified in a singular perturbation framework [19]

The initialization procedure covers cases when the energy is preserved together with the power flow, or when energy is dissipated at a change of modes. To allow bond graph modeling of other cases, like an elastic collision between rigid bodies, the constitutive relation has to be extended with a parameter describing the amount of energy that is conserved across the change of mode.

In a switch bond graph model it is interesting to find the same type of causal information as in a classical bond graph, but without propagating causality in all mode specific bond graphs. By using bicausality, phenomena like causal conflicts and derivative causalities can be found when propagating causality in a single bond graph, and with an additional algorithm algebraic loops are detected [20].

Newton's pendulum

An application of bond graphs to hybrid modeling is described in [21]. The mechanical system shown in Figure 6.1, known as "Newton's pendulum" is simulated. If the change in velocity at collision is modeled as discontinuous the system becomes a hybrid one. A switched bond graph model is shown

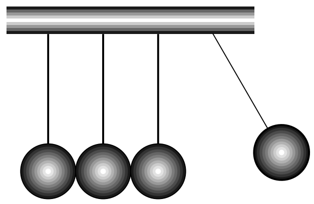


Figure 6.1: Newton's pendulum

inf Figure 6.2.

The simulation results are shown in Figure 6.3.

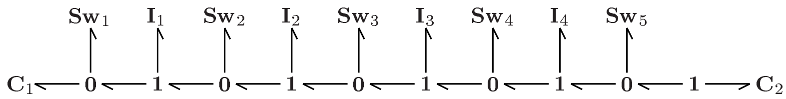


Figure 6.2: The switch bond graph model of Newton's pendulum.

6.2 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 proposed an approach for modeling and diagnosis of systems that fall in the area of discrete event dynamic systems [5]. 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:

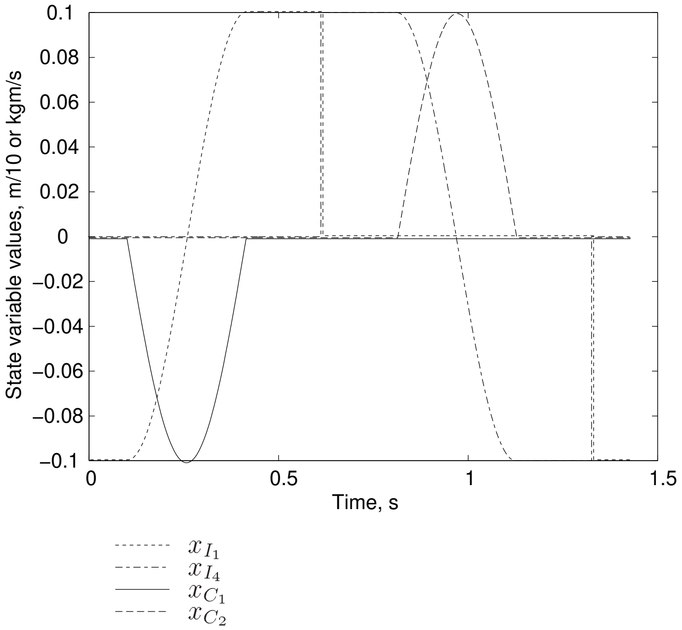
1. Modeling of the system to be diagnosed, by constructing a discrete event model containing both the normal and faulty behavior.

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

3. Analysis of diagnosability properties of the system.

Modeling

Components are modeled locally in reusable component models including both normal and faulty behavior. Faults are modeled as fault states with un-observable transitions to them, that a component can chose non-deterministically



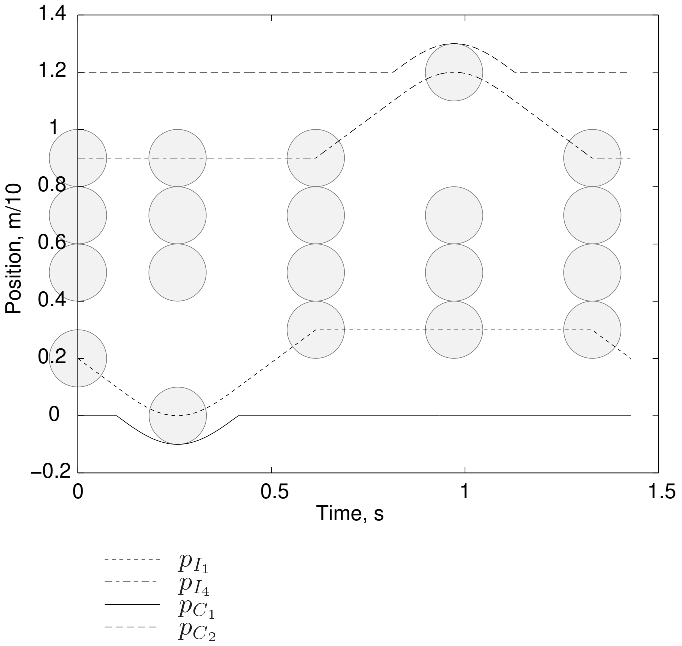


Figure 6.3: Simulation of Newton's pendulum.

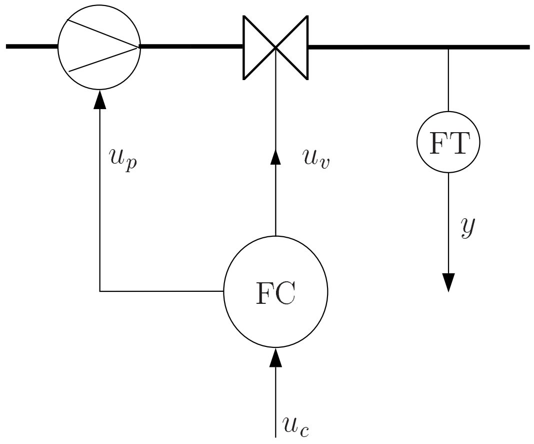


Figure 6.4: Flowchart of a simple system.

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 6.4. 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 6.5 for a FSM model of the valve. The other variables indicated in Figure 6.4 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 6.6.

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. This can be expressed as

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

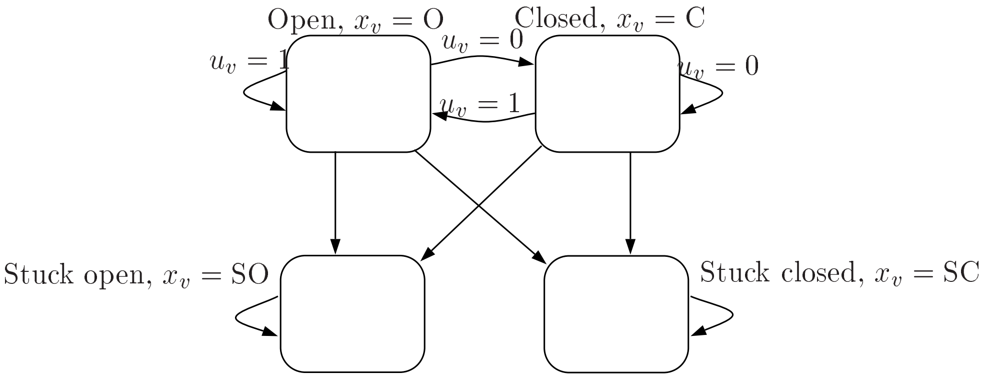


Figure 6.5: Valve component model with modeled faults, denoted $M_v(x_v, u_v, x_v^+)$.

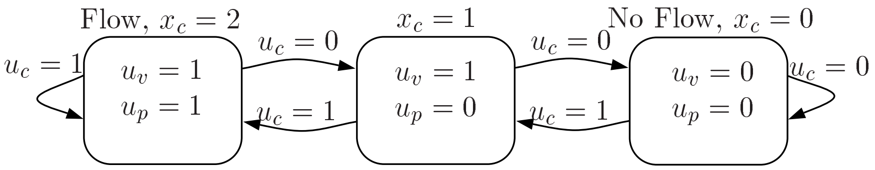


Figure 6.6: Controller for the valve/pump system, denoted $M_c(x_c, u_c, u_v, u_p, x_c^+)$.

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.

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 [5].

Diagnosability Analysis

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

A fault in the system is represented by a certain value of a component state variable. We say that the fault detection procedure is *ambivalent* with respect to a certain fault, when the normal value and the fault value of the component state variable variable is in the estimation set simultaneously, i.e., when the fault *and* normal behavior is consistent with the observations. The *ambivalent behavior* for a certain fault is then the nominal behavior for which the fault can not be detected, and this behavior is readily computable from the above relational system model M.

An example of the result of this kind of analysis is shown in Figure 6.7 and Figure 6.8. The indicator transition in Figure 6.8 is the transition that is necessary for the system to leave the ambivalent behavior. In this case, it means that the fault valve stuck closed, denoted $f_{v,\mathrm{SC}}$, can only be detected when the controller attempts to get flow through the system. This seems very reasonable. When the same analysis is performed for the fault valve stuck open, denoted $f_{v,\mathrm{SO}}$, we discover that this fault is undetectable, i.e., it can never be detected. The reason is that the controller never attempts to turn on the pump when the valve is supposed to be closed.

Fault Partitioning

In a system with many possible faults and a limited amount of sensors, it is often the case that the exact fault that has occured cannot be uniquely isolated. Without adding sensors or change something in the system to improve

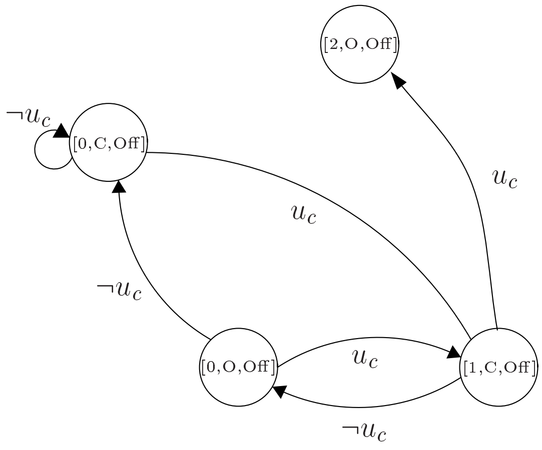


Figure 6.7: The ambivalent behavior for the fault valve stuck closed ($f_{v,\mathrm{SC}}$).

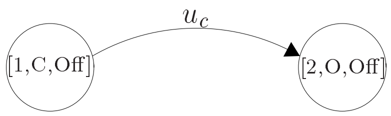


Figure 6.8: The indicator transition for the fault valve stuck closed ($f_{v,\mathrm{SC}}$).

diagnosability, we have to accept that certain faults cannot be distinguished and define a fault partition, i.e., a set of sets of faults.

Informally put, we say that two faults can be isolated if there exists a nominal state and input combination for which the output behavior for the two faults are different. As described in detail in [5], this property of a relational model M can be readily checked. To find all pairs of faults that cannot be distinguished, we have to perform all possible pairwise comparisons. The finest possible fault partition, under the single fault assumption, for which the faults in different partitions still are distinguishable, is then given by partitioning the faults with identical behavior together.

Performing this procedure on the valve/pump example gives the minimal partitioning

$$\{\{f_{v,\mathrm{SC}},\ f_{p,\mathrm{SOff}}\},\ \{f_{v,\mathrm{SO}}\},\ \{f_{p,\mathrm{SOn}}\}\},$$

i.e., the faults pump stuck off and valve stuck closed cannot be distinguished.

6.3 Fault Isolation in Control Systems with Object Oriented Architecture

Introduction

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

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 6.9.

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

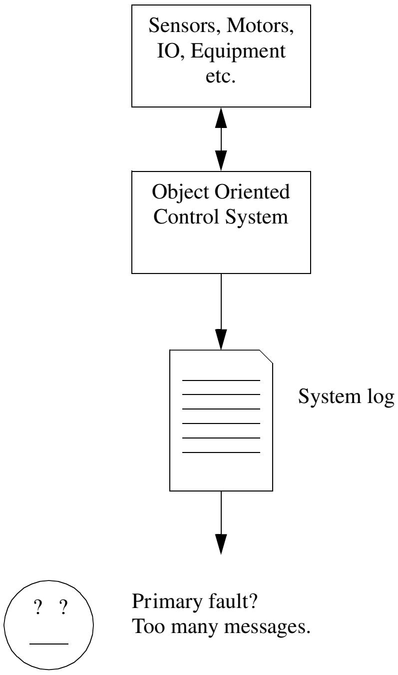


Figure 6.9: Problem overview

the operator's point of view in Figure 6.10.

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. A preliminary report on the studied problem is [123], and the approach is presented in detail in the report [126] and the thesis [5]. A patent application has also been filed with the swedish patent office (PRV) [65].

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 6.10.

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,

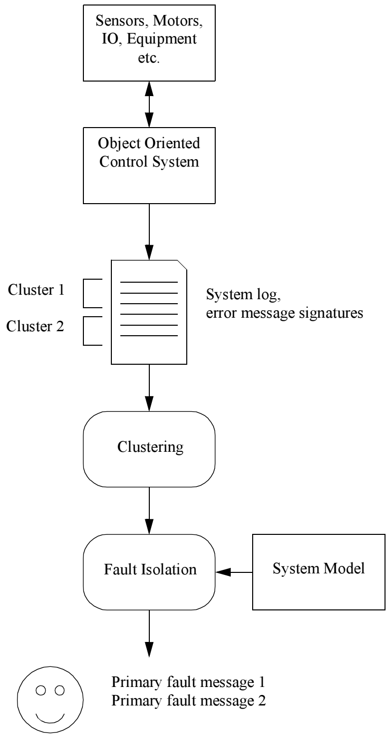


Figure 6.10: Main flow diagram of the fault isolation procedure

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 6.11. 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.

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.

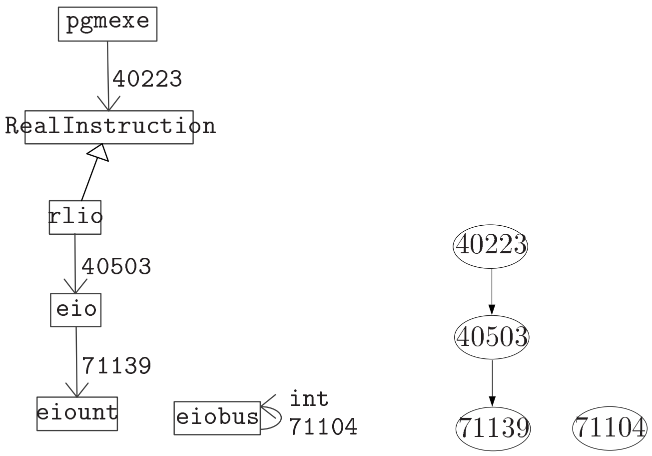
We formally represent a fault scenario with what we call a *base graph*, where the edges correspond to error messages, and the nodes correspond to objects, threads and packages in the run-time control system, as is explained in detail in [126, 5]. The base graph corresponding to the message log in

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

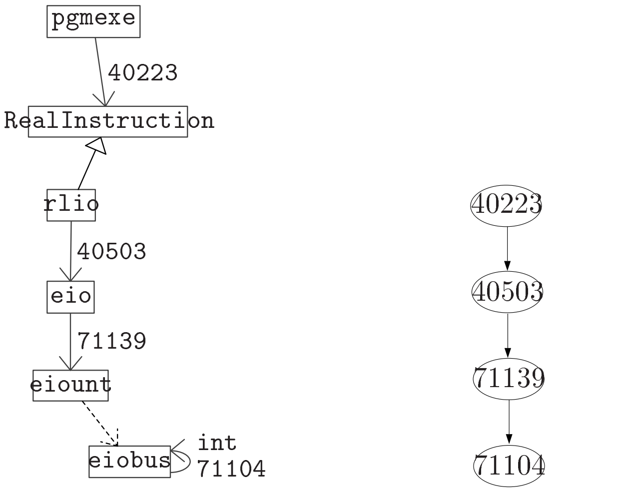
Figure 6.11 is automatically generated, and is shown in Figure 6.12(a). From the (initial) base graph in Figure 6.12(a), a cause-effect relation between the error messages can be derived by an automatic procedure. This cause-effect relation is represented by the graph in Figure 6.12(b), where the nodes are error messages.

As seen in Figure 6.12(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



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

Figure 6.12: The initial base graph and explanation graph for our fault scenario.



(a) Extended base graph. (b) Explanation graph.

Figure 6.13: The extended base graph and corresponding explanation graph for our fault scenario.

on services provided by the class `eiobus`, we can *extend* the initial base graph as shown in Figure 6.13(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 6.13(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.

6.4 Model Checking of Hybrid Systems

A special class of hybrid systems are mode switching systems, where system trajectories are continuous but may have discontinuous derivatives when switching between modes. Focusing on this class, and in particular those systems where the dynamics are governed by piecewise linear differential equations, we are able to perform certain analysis tasks.

Our analysis consists of verifying properties of these systems against a given specification. These properties typically have one of the two following characterizations: Given initial conditions, can we guarantee that

- the system will never enter certain "bad" modes?
- a certain sequence of modes will be executed?

This kind of analysis is typical in the context of discrete event dynamic systems, what we do is extend the procedure to mode switching systems. This is done using conservative approximations of the behavior of the continuous part of the dynamics. Basically, that means that we need to find outer and inner approximations of reachable sets and regions of attractions, respectively. These approximations are done using sets which facilitate computation and computer representation. Having computed these sets, we can check if they intersect transition surfaces leading to new modes and repeat the procedure for the next modes.

An important property of this approach is that it is completely automated. That is, given a model and a specification, the verification algorithm should answer whether the specification is fulfilled or not. And in those cases it is not, we would like the algorithm to present us with an explanation of what went wrong.

In contrast to finite state discrete event systems, where model checking algorithms are guaranteed to terminate with a correct answer, negative or positive, in a finite number of steps, we have no guarantees that we will succeed in verifying a specification. We do know that if we get a positive answer, then it is correct, but those cases when we fail may be due to actual errors in the system/controller design or they might be a result of the fact that we made approximations of the continuous behavior.

The restriction to linear dynamics and switching surfaces facilitates use of efficient computation tools such as linear programming and convex optimization using LMIs. This enables us to handle problems of interesting complexity.

Further details are presented in [69] and [37].

Chapter 7

Applications

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

7.1 Cellular Radio Systems

The global communications system today (the telephone system yesterday) is considered as the largest man-made system all categories. While the demand for access to services in such systems is exponentially growing, an increased interest in utilizing the available resources efficiently can be observed. In this project, the subset of wireless cellular communications systems will be in focus.

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

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

For practical reasons, the powers have to be computed locally for each connection using local feedback, though performance and stability depend

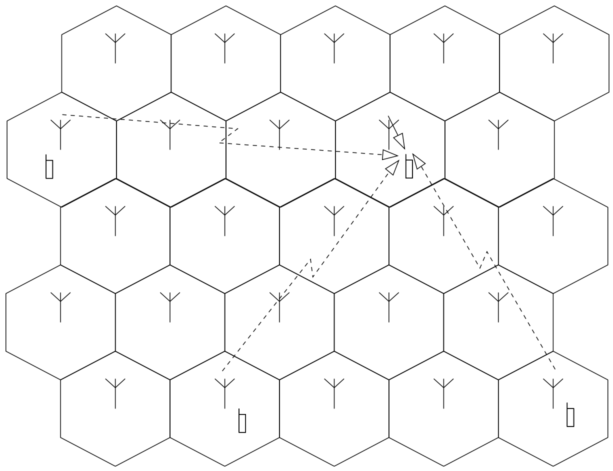


Figure 7.1: The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

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 control the powers to obtain a sufficient *signal-to-interference ratio (SIR)* γ, which is the useful received power C divided by the harmful power, or interference power I (including thermal noise). In dB, SIR $\gamma_{dB} = C_{dB} - I_{dB}$. The reference values, typically referred to as target SIR:s, are denoted by γ^t.

Two important feedback situations are typically considered:

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

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

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

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

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

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

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

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. With decision feedback, the local loops can be considered as linear except for relay feedback. 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.

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.

- 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.

These issues are addressed in [54, 49]. Some results on local design are presented in [50, 51, 53].

For example, consider a situation with only two mobiles. A signal intended for a particlar mobile is experienced as interference by the other together with thermal noise. The controller has to be strictly proper for practical reasons. In addition, a time delay of one sample is considered. Initially, the controllers are using powers to correspond to SIR:s of 10 dB. After 10 s, one mobile upgrade this to 16 dB. Simulation results using different control strategies are found in Figure 7.2. From the simulation, we note the following:

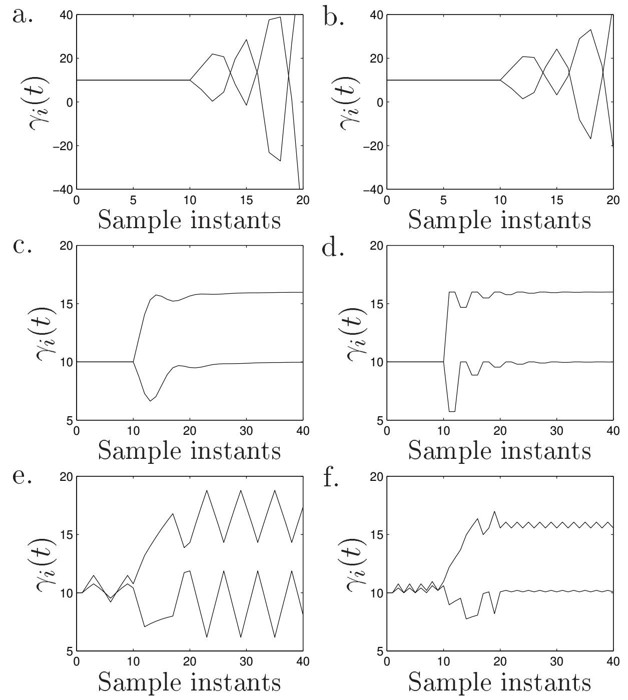


Figure 7.2: The recovering ability of various controllers when one of the two mobiles upgrades his target SIR from 10 to 16 dB. Information feedback: a-d. Decision feedback, e-f.

a. Information feedback using an existing algorithm (essentially an integrator), which have good performance when not considering time delays. Local analysis reveal that the algorithm is locally unstable, which yields an unstable global system.

b. A smaller controller gain yields stable local loops, but the global system is still unstable. This illustrates the fact that local stability is necessary but not sufficient for global stability.

c. An even smaller controller gain will always result in a stable global system.

d. Together with the Smith predictor, the controller a) corresponds to a stable system.

e. Decision feedback always result in an oscillative behavior, even when perfectly initialized.

f. The oscillations in the decision feedback case can be reduced by employing the Smith predictor.

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

7.2 Robot Control

This project 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 aim of the project is to study and develop methods for improvement of the performance of robot control systems.

Iterative Learning Control

In this work the focus has been on analysis and implementation of Iterative Learning Control (ILC), which is a method that is applicable where the system is carrying out the same operation iteratively. This is a common situation in many robot applications.

The structure of the problem that is considered is shown in Figure 7.3. The system G is controlled by a conventional control system including both feed-forward and feed-back, represented by the F_f and F respectively. 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.

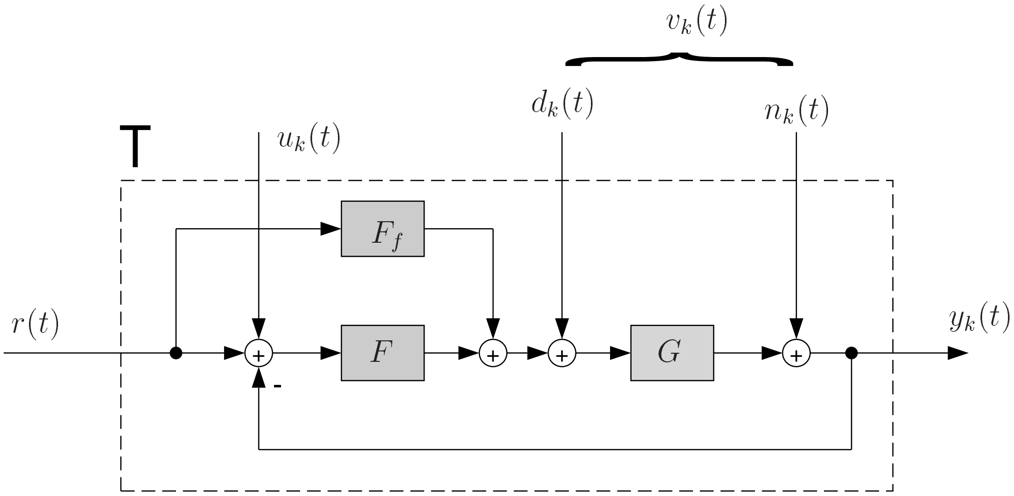


Figure 7.3: Control system

The project involves both theoretical studies and implementation. Some theoretical aspects that have been studied recently are ILC algorithms based on optimization and so called second order ILC algorithms. In the first area the algorithm for updating the correction signal $u_k(t)$ is derived by minimization of a quadratic criterion. In [30] it is shown how such algorithm can be interpreted in the frequency domain. Experiments carried out on an ABB IRB 1400 are also presented.

In second order ILC algorithms the ILC input signal in the next iteration $u_{k+1}(t)$ is formed using no only the latest error signal $e_k(t)$ but also the error from the previous iteration, i.e. $e_{k-1}(t)$. This idea has been proposed in a more or less ad hoc manner as a way of improving the performance in ILC. In [24] some initial work is presented where an approach for analysis of second order ILC algorithm is discussed.

As a complement to the theoretical studied extensive experiments on an ABB IRB 1400 have been carried out. Some of these results can be found in [111].

Control of Flexible Systems

It is inevitable that industrial robots will contain flexibilities in links and gears. Control of such systems is therefore an important research topic.

In [47] LQG control of a two-mass system is studied under the assumption that only the position of the first mass, corresponding to the motor, can be measured.

Iterative Tuning of Controllers

In this work Iterative Feedback Tuning (IFT) is used for tuning of the controller parameters in a simulation model of a two-link robot arm. Some of the results are presented in [29].

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`

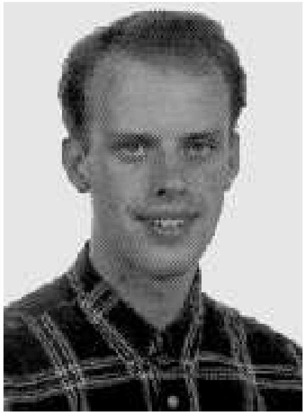
Inger Klein is a lecturer at the department. She was born in 1964. She received her M.Sc. in 1987, her Licentiate's degree in 1990, and her Ph.D. in 1993, all from Linköping University. Her research interest is Discrete Event Systems and Sequential Control.
`email: inger@isy.liu.se`

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`

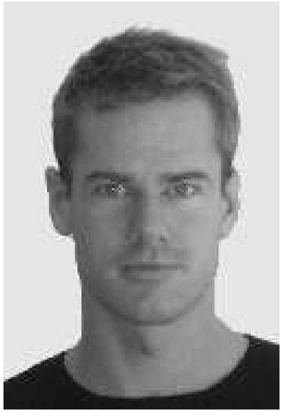
Anders Helmersson was born in 1957. In 1981, he received his M. Sc. in Applied Physics at Lund Institute of Technology. He has been with Saab Ericsson Space since 1984. In 1993 he joined the Control Group where he received his Ph.D in 1995. His research interest is mainly in robust control and gain scheduling. He is currently employed by Saab AB and an adjunct professor at the Division of Automatic Control.
`email: andersh@isy.liu.se`

Krister Edström was born in 1969. He received his M.Sc.in Applied Physics and Electrical Engineering in 1993, his Lic.Eng. in 1996 and his Ph.D. in 1999 all from Linköping University. He is currently employed by Ericsson Mobile Communications AB, Lund.
`email: edstrom@isy.liu.se`

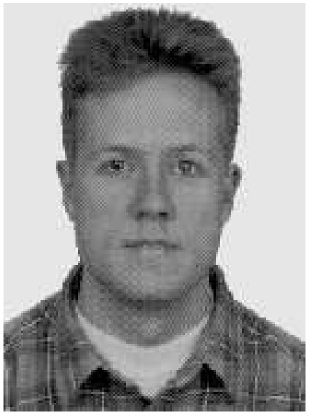


Anders Stenman was born in Gävle, Sweden in 1966. He received his M.Sc. in Computer Science and Engineering in 1993, his Lic.Eng. in Automatic Control in 1997 and his Ph.D. in 1999 all at Linköping University. His current research interest is local polynomial modeling and its use in identification and control.
email: stenman@isy.liu.se

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

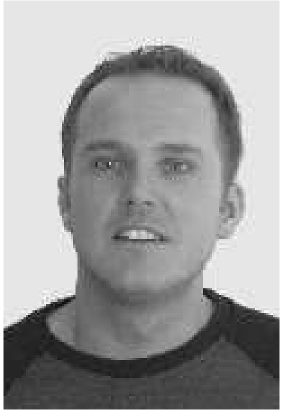


Urban Forssell was born in 1970. He received his M.Sc. degree in Applied Physics and Electrical Engineering in 1995, his Lic.Eng. in 1997 and his Ph.D. in 1999 all at Linköping University. His research interests include control-relevant identification and robust filtering. He is now employed by Mecel AB, Åmål, Sweden.
email: ufo@isy.liu.se

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

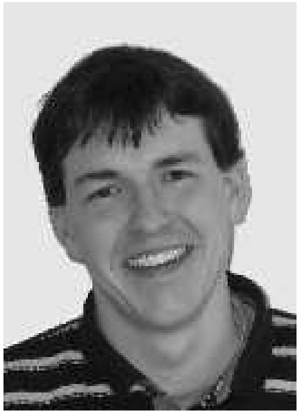
Mikael Norrlöf was born in 1971. He received his M.Sc in Computer Science and Engineering 1996 and his Lic.Eng. in 1998 both at Linköping University. His current research interests include Iterative Learning Control as well as modeling, and identification of industrial robots.
`email: mino@isy.liu.se`

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 and his Lic.Eng. in 1998 both at Linköping University. His current research interest is modeling and control of nonlinear systems.
email: `valure@isy.liu.se`



Per Spångéus was born in 1972. He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 and his Lic.Eng. in 1998 both at Linköping University. His current research interest is in the field of nonlinear systems.
email: `per@isy.liu.se`

Fredrik Gunnarsson was born in 1971 He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 and his Lic.Eng. in 1998 both at Linköping University. His current research interest is in the field of Radio Network Control.
email:fred@isy.liu.se



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

Johan Löfberg was born in 1974. He received his M.Sc. in Mechanical Engineering in 1997 at Linköping University.
`email:johanl@isy.liu.se`

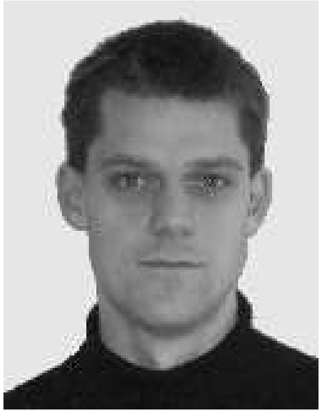
Ola Härkegård was born in 1973. He received his M.Sc. Applied Physics and Electrical Engineering in 1998 from Linköping University.
email:ola@isy.liu.se

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.
email:mans@isy.liu.se

Jonas Elbornsson was born in 1975. He received his M.Sc. in Applied Physics and Electrical Engineering in 1998 at Linköping University.
email:jonas@isy.liu.se

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.
email:roll@isy.liu.se

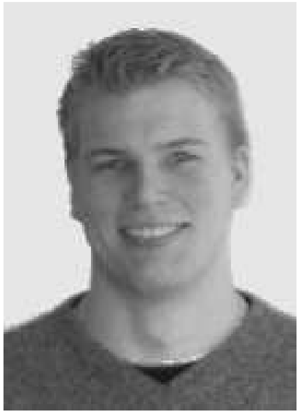
Rickard Karlsson was born in 1970. He received his M.Sc. in Applied Physics and Electrical Engineering in 1996 at Linköping University.
`email:rickard@isy.liu.se`



Per-Johan Nordlund was born in 1971. He received his M.Sc. in Applied Physics and Electrical Engineering in 1997 at Linköping University.
`email:perno@isy.liu.se`

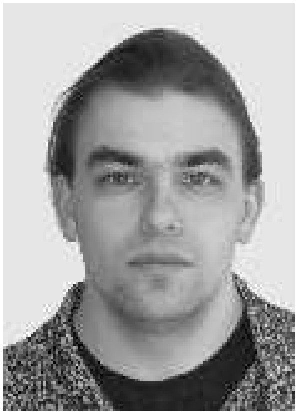
Jonas Jansson was born in 1973. He received his M.Sc. in Applied Physics and Electrical Engineering in 1999 from Linköping University.
email:jansson@isy.liu.se

Niclas Persson was born in 1975. He received his M.Sc. in Applied Physics and Electrical Engineering in 2000 from Linköping University.
email:persson@isy.liu.se



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 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

Martin Braun, Arizona State University was visiting Ph.D.-student at the Division during August - November 1999.

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

Dr. Andrea Garulli, was visiting postdoctoral fellow at the Division during September 1999.

Dr. Sebusang Sebusang, University of Botswana was visiting postdoctoral fellow at the Division during September 1999.

Appendix B

Courses

B.1 Undergraduate Courses

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

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

  - M+TB Mechanical Engineering and Engineering Biology Programs. 190 participants. Lecturer: Anna Hagenblad.
  - Y Applied Physics and Electrical Engineering. 150 participants. Lecturer: Torkel Glad.
  - D Computer Engineering Program. 120 participants. Lecturer: Urban Forssell.
  - 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: Lennart Ljung.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management and Mechanical Enginnering 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. 20 participants. Lecturer: Svante Gunnarsson.
- *Digital Signal Processing* (Digital Signalbehandling). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Spectral analysis, Filtering, Signal Modeling, Wiener and Kalman filtering, Adaptive filters. 60 participants. Lecturer: Fredrik Gustafsson.
- *Modelling and Simulation* (Modellbygge och Simulering). For the Applied Physics and Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 65 participants. Lecturer: Torkel Glad.
- *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: Inger Klein.
- *Digital Control* (Digital Styrning). For the Applied Physics and Electrical Engineering, Computer Science and Engineering and Industrial Engineering and Management Programs. Numerical control, binary control and PLCS, process computers and applications of digital process control. 90 participants. Lecturers: Tomas McKelvey et al.
- *Real Time Process Control* (Realtidsprocesser och reglering). For the Information Technology Program. Real time systems. PID control. 25 participants. Lecturer: Inger Klein.
- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, controllability, observability, feedback control. 25 participants. Lecturer: Inger Klein.
- *Control Project Laboratory* (Reglerteknisk projektkurs) For the Applied Physics and Electrical Engineering and Computer Science and

Engineering Programs, Modelling and identification of laboratory processes, Controller design and implementation, 15 Participants. Lecturer: Fredrik Gustafsson.

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

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

- *Robust Multivariable Control*. Lecturer: Anders Helmersson. Literature: Zhou, Doyle and Glover, Robust and Optimal Control, Prentice Hall, 1995, ISBN 0-13-456567-3

- *Nonlinear Control Systems*. Lecturer: Torkel Glad. Literature: Lecture notes.

- *ENSYM Project Oriented Study*. Course leader: Lennart Ljung.

- *Object Oriented Languages for Dynamic Systems.* Course leaders: Peter Fritzson and Torkel Glad. 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 Mattias Olofsson.

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 Texas TravelMate 3000 WinSX
- 2 Texas TravelMate 4000 WinSLC
- 2 Texas TravelMate 4000 WinDX2
- 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 hot water heating process
- 1 coupled tanks process, Tecquipment CE5
- 1 ball and beam process, Tecquipment CE6
- 1 ball and hoop process, Tecquipment CE9
- 1 coupled drives process, Tecquipment CE108
- 3 Lego processes for sequential control
- 1 helicopter-like process
- 2 wind meter processes from Chalmers Institute of Technology
- 8 Dell Workstation 400 with dSPACE signal processing cards
- 6 Pentium 120 PC
- 3 AST Bravo 486 computers with Allan Bradley SLC500 PLC system
- 1 LEO 386 computers with Metrabyte Dash 16 interfaces (A/D, D/A and digital I/O).
- 1 HP LaserJet 4 MP laser printer

Appendix D

Seminars

- *Signalspaning på kortvåg.* **Peter Nagy**, FOA, Linköping, January 14, 1999.

- *Some approaches on how to identify continuous-time processes.* **Torsten Söderström**, Uppsala University, January 21, 1999.

- *Elastic Industrial Robots: Modelling and Identification.* **Geir Hovland**, ABB Corporate Research, February 4, 1999.

- *Geometric aspects of interest rate theory.* **Tomas Björk**, Stockholm School of Economics, March 4, 1999.

- *Scandicraft System, a UAV company.* **Magnus Sundstedt**, Scandicraft Systems, March 25, 1999.

- *Formella metoder, automater och automation.* **Martin Fabian**, Chalmers University of Technology, April 22, 1999.

- *Curve fitting with the Hough transform, an application in dialysis dose quantification.* **Jan Sternby**, Gambro AB, Lund, April 29, 1999.

- *A conditional bootstrap approach to model selection.* **Ola Hössjer**, Lund University, May 7, 1999.

- *Validation of Robust Control Models.* **Roy Smith**, University of California, Santa Barbara, May 17, 1999.

- *Linear and Nonlinear Model Validation in Various Domains.* **Roy Smith**, University of California, Santa Barbara, May 17, 1999.
- *Blind multi user detection and stochastic scheduling problems.* **Vikram Krishnamurthy**, Melbourne University, May 20. 1999.
- *EM Algorithm for State and Parameter Estimation – Structural Results.* **Vikram Krishnamurthy**, Melbourne University, May 20, 1999.
- *Bond graph Aided Design of Controlled Systems.* **Geneviève Dauphin-Tanguy**, Ecole Centrale de Lille, France, May 27, 1999.
- *On Weighting and Pre-filtering in Subspace-based Identification.* **Tony Gustavsson**, Chalmers University of Technology, June 3, 1999.
- *System Identification: State-space versus Transfer Function.* **Magnus Jansson**, Royal Institute of Technology, Stockholm, June 8, 1999.
- *Worst Case Identification.* **Paresh Date**, University of Cambridge, June 23, 1999.
- *Challenges for formal methods in process control engineering.* **Stefan Kowalewski**, University of Dortmund, August 9, 1999.
- *Verification of logic controlled continuous processes.* **Stefan Kowalewski**, University of Dortmund, August 10, 1999.
- *Planning and Control: A perspective from Artificial Intelligence.* **Hector Geffner**, Universidad Simón Bolívar, Venezuela, August 13, 1999.
- *Identification of a linear regressive equation.* **Yulia Gel**, Mälardalen University, Västerås, August 19, 1999.
- *Planning and Control: A Perspective from AI (part 2).* **Hector Geffner**, Universidad Simón Bolívar, Venezuela, August 20, 1999.
- *Modeling and Control of Atomically Engineered Materials.* **Robert Kosut**, SC Solutions, Inc, Mountain View, CA, August 23, 1999.
- *Unfalsified Adaptive Control.* **Robert Kosut**, SC Solutions, Inc, Mountain View, CA, August 24, 1999.

- *Trajectory Exploration for Nonlinear Control Systems with application to Aggressive Flight Maneuvers.* **John Hauser**, Univ of Colorado/Caltech, September 2, 1999.

- *When and Why?* **Tobias Adolfsson**, Chalmers University of Technology, Göteborg, September 2, 1999.

- *Gain Wind-up in MRAC Control: The Minimal Control Synthesis (MCS) Algorithm Work Around.* **Sebusang Sebusang**, University of Botswana, September 9, 1999.

- *Set membership estimation: theory and applications (part I).* **Andrea Garulli**, Universita' degli Studi di Siena, Siena, Italy, September 16, 1999.

- *Set membership estimation: theory and applications (part II).* **Andrea Garulli**, Universita' degli Studi di Siena, Siena, Italy, September 20, 1999,

- *Planning of computer experiments.* **Jacques de Mare**, Chalmers University of Technology, Göteborg, October 7, 1999.

- *Mobile Robot Research at Utah State University.* **Kevin L. Moore**, Utah State University, October 13, 1999.

- *An Introduction to Iterative Learning Control.* **Kevin L. Moore**, Utah State University, October 14, 1999.

- *An Introduction to Model Checking.* **Bengt Jonsson** Uppsala University, October 26, 1999.

- *Utilizing "Model-on-Demand" for Model Predictive Control in the Process Industries.* **Martin Braun**, Arizona State University, October 28, 1999.

- *Subspace based fatigue detection under operating conditions.* **Albert Benveniste**, IRISA, France, November 3, 1999.

- *Object-Relational Databases and Telecommunication Network Management.* **John Baras**, University of Maryland, College Park, MD, November 3, 1999.

- *Identification for Control - A comparison of different approaches for the model error.* **Wolfgang Reinelt**, University of Paderborn, Germany, November 11, 1999.

- *Minimizing the effect of out of bandwidth modes in models of reverberant systems that arise in modal analysis.* **Reza Moheimani**, University of Newcastle, Newcastle, Australia, November 25, 1999.

- *Initialization of Non-Linear Grey- & Black-Box Models.* **Jonas Sjöberg**, Chalmers University of Technology, Göteborg, November 29, 1999.

- *Diagnostics and performance assessment for process industry controls.* **K. Forsman**, ABB Automation Systems, November 29, 1999.

Appendix E

Travel and Conferences

Niclas Bergman participated in the Second Int. Conf. on Multisource Multisensor Fusion (FUSION'99) July 6-8, Sunnyvale California, USA, 1999, the European Control Conference (ECC'99), 31 August - 3 September, Karlsruhe, Germany, 1999. He was visiting researcher 6 October - 17 November, Department of Electronic and Electrical Engineering, Melbourne University, Australia. and visiting researcher 18 November - 2 December, Department of Electrical and Computer Engineering, Newcastle, Australia. On December 16-18 he participated in the Workshop on Sequential Monte Carlo methods, December 16-18, Cambridge University, Cambridge, UK, 1999.

Krister Edström participated in 1999 International Conference on Bond Graph Modeling and Simulation in San Francisco, California, USA, January 17-20. In October 18-19 he took part in the SSC Conference on Simulation and Modeling, Linköping, Sweden.

Valur Einarsson was visiting researcher April 19 - May 13, Electrical and Computer Engineering Department, Carnegie Mellon University, Pittsburgh, PA, USA, participated in American Control Conference (ACC'99), June 2-4, San Diego, CA, USA and was visiting researcher August 30 - October 29, Electrical and Computer Engineering Department, Carnegie Mellon University, Pittsburgh, PA, USA.

Jonas Elbornsson participated in the European Control Conference, ECC'99 in Karlsruhe, Germany, August 31 - September 3, 1999.

Torkel Glad took part in the Åström Symposium in Lund on August 27-27 and in the European Control Conference in Karlsruhe, Germany August 31 - September 3.

Fredrik Gunnarsson participated in the IEEE Vehicular Technology Conference, Houston, TX, USA, May 17-20, 1999, and he visited Wireless Information Network Laboratory, Rutgers University, NJ, USA on May 21. June 14-16 he took part in the RVK Workshop, Karlskrona, Sweden, and July 4 - 9 he participated in the IFAC World Congress in Beijing, China. October 21 - 22 he took part in the Conference on Computer Science and Systems Engineering (CCSSE'99), in Norrköping, Sweden.

Svante Gunnarsson participated in the IFAC World Congress, Beijing, China, 5 - 9 July, 1999 and the IEEE Conference on Decision and Control, Phoenix, Arizona, 7 - 10,December, 1999.

Fredrik Gustafsson participated in ICASSP'99 in Phoenix, Arizona, March 14 - 19, 1999, he visited the Royal Institute of Technology in Stockholm on April 8 and Ericsson Radio Systems AB in Kista, Sweden on April 28. June 15-16 he participated in the RVK Workshop in Karlskrona, Sweden and July 4 - 9 he took part in the IFAC World Congress in Beijing, China. September 7 he participated in the NUTEK Workshop on Data Networks in Stockholm, Sweden and October 21 - 22 in the Conference on Computer Science and Systems Engineering (CCSSE'99), in Norrköping, Sweden. On December 17 he was faculty opponent at Uppsala University, Uppsala, Sweden.

Anna Hagenblad participated in MED'99 in Haifa, Israel, June 28-30, in ERNSI'99 in Théoule, France, September 27-29 and CCSSE'99, Norrköping, Sweden, October 21-22.

Anders Helmersson particpated in the IFAC World Congress in Beijing, China, July 4 - 9.

Ola Härkegård participated in the European Control Conference (ECC'99), August 31 - September 3, Karlsruhe, Germany, 1999 and the Conference on Computer Science and Systems Engineering (CCSSE'99), October 21-22, Norrköping, 1999

Ingela Lind took part in the European Control Conference (ECC'99), 31 August - 3 September, Karlsruhe, Germany, 1999

Lennart Ljung visited MIT, Cambridge, MA, on April 27 - 29. June 21 - 23 he participated in the Dutch Summer School on Identification for Control in Veldhoven, NL. July 4 - 10 he participated in the IFAC World Congress in Beijing. August 27 - 28 he took part in the Åström Symposium on Control in Lund, Sweden. September 3 - 4 he participated in the European Union

Control Council Meeting in Karlsruhe, Germany. September 6 - 9 he tok part in the 6th St Petersburg Symposium on Adaptive Systems Theory (SPAS'99) in St Petersburg, Russia. September 26 - 30 he participated in the European Union Research Network on System Identification, ERNSI, Annual Meeting in Théoule, France. October 21 and 22 he participated in the Conference on Computer Science and Systems Engineering, Norrköping, Sweden. November 25 and 26 he visited University of Barcelona as a member of the Tribunal for Josefina Lopez. December 6 - 9 he participated in the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 7–10,

Tomas McKelvey Visit at the Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden May 29-30, 1999 on June 21-23 he visited the Department of Econometrics and Operations Research, Technical University of Vienna, Austria and participated in the IFAC World Congress, Beijing, China, July 5 -9. From August 2, 1999 he was Visiting academic at the Department of Electrical and Computer Engineering, University of Newcastle, Australia. He also participated in 38th IEEE Conference on Decision and Control, Phoenix, Arizona, USA, December 7-10, 1999.

Mikael Norrlöf participated in the 38th Conference on Decision and Control (CDC'99), December 7-10, Phoenix, Arizona, USA and the Second Conference on Computer Science and Systems Engineering in Linköping, October 21-22, 1999, Norrköping, Sweden.

Wolfgang Reinelt visited the Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 26-27 April 1999, the Automatic Control Group, Paderborn University, Paderborn, Germany, 29-30 April 1999. He participated in the International Symposium on Quantitative Feedback Theory and Robust Frequency Domain Methods, Durban, South Africa, 26-27 August 1999 the European Control Conference, Karlsruhe, Germany, 31 August-3 September 1999 and the 8th ERNSI Workshop System Identification, 27-29 September 1999, Villa Saint Camille, Theoule, France. On November 3 he visited the Department of Signals, Sensors and Systems. Royal Institute of Technology, Stockholm, Sweden and participated in the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA. 7-10 December 1999.

Jacob Roll took part in the Course in Convex Optimization by Professor Stephen Boyd, June 16 - 18 in Stockholm, Sweden the European Control

Conference (ECC'99), 31 August - 3 September, Karlsruhe, Germany, 1999 and in the 2nd CCSSE, Norrköping, Sweden, October 21-22, 1999.

Ulla Salaneck participated in Rikssekreterarträffen in Noordwijk, Holland, September 19-22 and ERNSI'99 in Théoule, France, September 27-29.

Anders Stenman participated in the 14th World Congress of IFAC, Beijing, P.R. China, July 5–9. In September 27–29 he took part in the 8th ERNSI Workshop on System Identification, Théoule, France. He also attended the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 7–10.

Fredrik Tjärnström participated in the 8th ERNSI Workshop on System Identification September 27–29,Théoule, France, the 2nd CCSSE, Norrköping, Sweden, October 21-22, 1999 and the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 7–10.

Måns Östring participated in the European Control Conference (ECC'99), 31 August - 3 September, Karlsruhe, Germany and in CCSSE'99, Norrköping, Sweden, October 21-22.

Appendix F

Lectures by the Staff

- Niclas Bergman: *Three Statistical Batch Algorithms for Tracking Manoeuvring Targets* ECC'99, European Control Conference (ECC'99), 31 August - 3 September, Karlsruhe, Germany, 1999

- Niclas Bergman: *Constructive Bayesian Nonlinear Filtering* Department of Electrical and Computer Engineering, Newcastle, Australia

- Niclas Bergman: *Posterior Cramer-Rao Bounds for Sequential Estimation* Workshop on Sequential Monte Carlo methods, December 16-18, Cambridge University, Cambridge, UK, 1999

- Valur Einarsson: *Verification of Piecewise Linear Systems using Abstractions* CMU, Electrical and Computer Engineering Department, Carnegie Mellon University, Pittsburgh, PA, USA

- Valur Einarsson: *Verification of Piecewise Linear Switched Systems using Abstractions* ACC'99, American Control Conference (ACC'99), June 2-4, San Diego, CA, USA.

- Torkel Glad: *Extensions of the RGA concept to nonlinear systems* European Control Conference, Karlsruhe, Germany, August 31.

- Fredrik Gunnarsson: *Local Methods for Design and Analysis of Power Control Algorithms* Radio Communication Systems Group, Royal Institute of Technology, Stockholm, Sweden, April 8, 1999.

- Fredrik Gunnarsson: *Pole Placement Design of Power Control Algorithms* IEEE Vehicular Technology Conference, Houston, Texas, USA, May 17, 1999.

- Fredrik Gunnarsson: *Estimation of the Carrier-to-Interference Ratio in Cellular Radio Systems* IEEE Vehicular Technology Conference, Houston, Texas, USA, May 18, 1999.

- Fredrik Gunnarsson: *Improved Performance Using Nonlinear Components in Power Control Algorithms* IEEE Vehicular Technology Conference, Houston, Texas, USA, May 18, 1999.

- Fredrik Gunnarsson: *Local Methods for Design and Analysis of Power Control Algorithms* Wireless Information Network Laboratory, Rutgers University, New Jersey, USA, May 21, 1999.

- Fredrik Gunnarsson: *Power Control in Cellular Radio Systems - Analysis and Design* RadioVetenskap och Kommunikation, Karlskrona, Sweden, June 15 1999.

- Fredrik Gunnarsson: *A Concept of Power Control in Cellular Radio Systems* IFAC World Congress, Beijing, China, July 5 1999.

- Fredrik Gunnarsson: *Parameter Estimation in Cellular Radio Systems* Conference on Computer Science and Systems Engineering in Linköping, Norrköping, Sweden, October 20, 1999.

- Svante Gunnarsson: *Iterative Feedback Tuning Applied to Robot Joint Controllers*, IFAC World Congerss, Beijing, China, 9 July, 1999.

- Svante Gunnarsson: *Some Aspects of an Optimization Approach to Iterative Learning Control* EEE Conference on Decision and Control, Phoenix, Arizona, 8 December, 1999.

- Anna Hagenblad: *Initialization and model reduction for Wiener model identification*, 7th Mediterranean Conference on Control and Automation, Haifa, Israel, June 28-30, 1999.

- Ola Härkegård: *Longitudinal Aircraft Control Using Backstepping* CCSSE'99, Norrköping, Sweden, October 21, 1999.

- Magnus Larsson: *Fault Isolation in Object Oriented Control Systems* ABB Robotics AB, Västerås, January 26, 1999.
- Lennart Ljung: *System Identification - Times Series Analysis for Control People*, Department of Mathematics, Chalmers University, Göteborg, Sweden, March 4, 1999.
- Lennart Ljung: *Model Validation and Model Error Models*, MIT, Cambridge, MA. April 29, 1999.
- Lennart Ljung: *A Bayesian Approach to Terrain-Aided Navigation*, Lund Institute of Technology, Lund Sweden, March 26, 1999.
- Lennart Ljung *System Identification - State of the Art* The Dutch Summer School on Identification for Control, June 21, 1999.
- Lennart Ljung *Model Quality and Experiment Design* The Dutch Summer School on Identification for Control, June 21, 1999.
- Lennart Ljung: *Model Validation and Model Error Modeling* August 28, 1999.
- Lennart Ljung: *On the Accuracy of Recursively Estimated Models of Time Varying Systems* SPAS'99, St Petersburg, Russia, September 6, 1999.
- Lennart Ljung: *Minimizing the Variance of Transfer Functions* SPAS'99, St Petersburg, Russia, September 7, 1999.
- Lennart Ljung: *System Identification - the Past, the Present and the Future*, The 8th ERNSI Workshop on System Identification, Théoule, France, September 27.
- Lennart Ljung: *Estimation Focus in Identification:Prefiltering, Noise-models and Prediction*, 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA December 9, 1999.
- Lennart Ljung: *Model Validation and Model Error Models*, Uppsala University, February 10, 1999.
- Lennart Ljung: *Model Validation and Model Error Models* Royal Institute of Technology, Stockholm, April 12, 1999.

- Johan Löfberg: *Backstepping with local LQ performance and global approximation of quadratic performance* CSSE99. Norrköping, Sweden,

- Tomas McKelvey: *Dynamic minimal parametrizations of multivariable linear systems* , Department of Econometrics and Operations Research, Technical University Vienna, Austria, June 22, 1999.

- Tomas McKelvey: *Subspace based System Identification in Time and Frequency Domain*, Department of Statistics, University of Newcastle, Australia, September 15, 1999.

- Tomas McKelvey: *Dynamical parametrizations of multivariable linear systems*, Department of Electrical and Computer Engineering, University of Newcastle, Australia, October 13, 1999.

- Tomas McKelvey: *MA estimation in polynomial time*, Dept. of Electrical and Computer Engineering, University of Newcastle, Australia, November 17, 1999.

- Tomas McKelvey: *MA estimation in polynomial time* , 38th IEEE Conference on Decision and Control, Phoenix, Arizona, USA, December 9, 1999.

- Tomas McKelvey: *Vector ARMA estimation: an enhanced subspace approach*, 38th IEEE Conference on Decision and Control, Phoenix, Arizona, USA, December 9, 1999.

- Mikael Norrlöf: *A Frequency Domain Analysis of a Second Order Iterative Learning Control Algorithm* 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA December 9, 1999.

- Mikael Norrlöf: *A model based Iterative Learning Control method applied to an industrial robot* CCSSE'99, Norrköping, Sweden, October 21, 1999.

- Wolfgang Reinelt: *Robust Control of Systems with Hard Constraints.* Seminar at Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, 27 April 1999

- Wolfgang Reinelt: *H -infinity Loop Shaping for Systems with Hard Bounds*. Symposium on Quantitative Feedback Theory and Robust Frequency Domain Methods, Durban, South Africa, 26-27 August 1999

- Wolfgang Reinelt: *Comparing different Model error concepts for identification for control*. 8th ERNSI Workshop System Identification, 29 September 1999, Villa Sainte Camille, Theoule, France.

- Wolfgang Reinelt: *Identification for control - a comparison of different approaches for the model error*. Seminar at Dept of Signals, Sensors and Systems. Royal Institute of Technology, Stockholm, Sweden, 3 November 1999

- Wolfgang Reinelt: *Comparing different model error concepts for identification for control*. ISY Seminar. Division of Automatic Control, Linköping University, Linköping, Sweden, 11 November 1999.

- Wolfgang Reinelt:*Model error concepts in identification for control*. (Invited Session on Model Set Theory for Robust Identification and Control) 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA. 8 December 1999.

- Jacob Roll: *Invariance of Approximating Automata for Piecewise Linear Systems*, CCSSE'99, Norrköping, Sweden, October 21-22, 1999.

- Anders Stenman: *On Adaptive Smoothing of Empirical Transfer Function Estimates*, The 14th World Congress of IFAC, Beijing, P.R. China, July 9.

- Anders Stenman: *Model on Demand: An approach to nonparametric and nonlinear black-box modeling*, The 8th ERNSI Workshop on System Identification, Théoule, France, September 27.

- Anders Stenman: *Model on Demand with Applications to Modeling and Control*, S3 Automatic Control, Royal Institute of Technology, Stockholm, Sweden, October 20.

- Anders Stenman: *Model on Demand – a Nonparametric Approach to Modeling and Control*, 1999 Symposium on Advanced Modeling, Scheduling, and Control Solutions, Arizona State University, Tempe, AZ USA, December 3.

- Anders Stenman: *Model-free Predictive Control.* The 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 10.

- Fredrik Tjärnström: *Model Reduction an Variance Reduction*The 8th ERNSI Workshop on System Identification, Théoule, France, September 27.

- Fredrik Tjärnström: *Bootstrap as a Tool in System Identification* CC-SSE, Norrköping, Sweden, October 21, 1999.

- Fredrik Tjärnström: *Estimating the Variance in Case of Undermodeling Using Bootstrap* The 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 10.

- Fredrik Tjärnström: *Comparison of Methods for Probabilistic Uncertainty Bounding* The 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA, December 10.

- Måns Östring: *LQG Control of a Flexible Servo* CCSSE'99, Norrköping, Sweden, October 21, 1999.

Appendix G

Publications

Ph.D. Theses

[1] Urban Forssell. *Closed-loop Identification: Methods, Theory, and Applications*. PhD thesis, Mar 1999.

[2] Anders Stenman. *Model on Demand: Algorithms, Analysis and Applications*. PhD thesis, SE-581 83 Linköping, Sweden, Apr 1999.

[3] Niclas Bergman. *Recursive Bayesian Estimation: Navigation and Tracking Applications*. PhD thesis, May 1999.

[4] Krister Edström. *Switched Bond Graphs: Simulation and Analysis*. PhD thesis, Linköpings Universitet, 581 83 Linköping, Sweden, May 1999.

[5] Magnus Larsson. *Behavioral and Structural Model Based Approaches to Discrete Diagnosis*. PhD thesis, Nov 1999.

Licentiate Thesis

[6] Anna Hagenblad. Aspects of the identification of wiener models. Technical Report Licentiate Thesis no. 793, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Nov 1999.

Journal Papers and Book Chapters

[7] Lennart Ljung and Urban Forssell. An alternative motivation for the indirect approach to closed-loop identification. *IEEE Transactions on Automatic Control*, pages 2206–2209, Oct 1999.

[8] Urban Forssell and Lennart Ljung. A projection method for closed-loop identification. *IEEE Transactions on Automatic Control, To appear*, Oct 1999. Preliminary version available as Technical Report LiTH-ISY-R-1984, Linköping University, Linköping,.

[9] Urban Forssell and Lennart Ljung. Identification of unstable systems using output error and Box-Jenkins model structures. *IEEE Transactions on Automatic Control, To appear*, Oct 1999.

[10] Urban Forssell and Lennart Ljung. Closed-loop identification revisited. *Automatica*, 35:1215–1241, June 1999.

[11] Niclas Bergman, Lennart Ljung, and Fredrik Gustafsson. Terrain navigation using bayesian statistics. *IEEE Control Systems Magazine*, 19(3):33–40, June 1999.

[12] A. Pogromsky, Torkel Glad, and H. Nijmeijer. On diffusion driven oscillations in coupled dynamical systems. *International Journal of Bifurcation and Chaos*, 9(4), Apr 1999.

[13] P. Lindskog and Lennart Ljung. Ensuring monotonic gain characteristics in estimated models by fuzzy model structure. *Automatica, to appear*, Feb 2000.

[14] Urban Forssell and Lennart Ljung. Some results on optimal experiment design. *Automatica, to appear*, May 2000.

[15] E. Pantelay, A. Loria, and A. Sokolov. Global uniform asymptotic stability of cascaded nonlinear non-autonomous systems. *European Journal of Control*, 5:107–115, Mar 1999.

[16] D. Huang and Fredrik Gustafsson. Sufficient output conditions for identifiability in blind equalization. *IEEE Transactions on Communications*, 47(2), Feb 1999.

[17] B. Ninness, H. Hjalmarsson, and Fredrik Gustafsson. The fundamental role of general orthonormal bases in system identification. *IEEE Transaction of Automatic Control*, 44(7), Mar 1999.

[18] B. Ninness, H. Hjalmarsson, and Fredrik Gustafsson. Bias and variance analysis of estimation using fixed denominator model structures. *SIAM Journal on Control and Optimization*, 37(2), Mar 1999.

Conference Papers

[19] Krister Edström. Generating state space equations from a bond graph with dependent storage elements using singular perturbation theory. In *Proc. of 1999 International Conference on Bond Graph Modeling and Simulation (ICBGM 99)*, volume 31, pages 105–110, San Francisco, CA, Jan 1999. SCS.

[20] Krister Edström. A causal propagation algorithm for switched bond graphs using bicausality. In *Proc. of 1999 International Conference on Bond Graph Modeling and Simulation (ICBGM 99)*, pages 77–82, San Francisco, CA, Jan 1999. SCS.

[21] Krister Edström. Simulation of newtons pendulum using switched bond graphs. In *Proc. of 1999 International Conference on Bond Graph Modeling and Simulation (ICBGM 99)*, volume 31, pages 283–287, San Francisco, CA, Jan 1999.

[22] Anna Hagenblad. Initialization and model reduction for wiener model identification. In *The 7th Mediteranean Conference on Control and Automation (MED99)*, Haifa, Israel, Jun 1999.

[23] Wolfgang Reinelt. H-inf loop shaping for systems with hard bounds. In *Int Symp on Quantitative Feedback Theory and Robust Frequency Domain Methods*, pages 89–103, Durban, South Africa, Aug 1999.

[24] Mikael Norrlöf and Svante Gunnarsson. A frequency domain analysis of a second order iterative learning control algorithm. In *Proc. of the 38th IEEE Conference on Decision and Control*, Pheonix, Arizona, USA, Dec 1999.

[25] Anders Stenman, Fredrik Gustafsson, D.E. Rivera, Lennart Ljung, and Tomas McKelvey. On adaptive smoothing of empirical transfer function estimates. In H.F. Chen and B. Wahlberg, editors, *Preprints of the 14th World Congress of IFAC, Beijing, P. R. China*, volume H, pages 415–420. Elsevier Science, Jul 1999.

[26] Fredrik Tjärnström and Lennart Ljung. Estimating the variance in case of undermodeling using bootstrap. In *Proceedings of the 38th IEEE Conference on Decision and Control*, Pheonix, Arizona, USA, Dec 1999.

[27] M.W. Braun, D.E. Rivera, Anders Stenman, W. Foslien, and C. Hrenya. Multi-level pseudo-random signal design and 'model-on-demand' estimation applied to nonlinear identification of a rtp water reactor. In *Preceedings of the 1999 American Control Conference, San Diego, USA*, pages 1573–1579, Jun 1999.

[28] Fredrik Tjärnström and Urban Forssell. Comparison of methods for probabilistic uncertainty bounding. In *Proceedings of the 38th IEEE Conference on Decision and Control*, Dec 1999.

[29] Svante Gunnarsson, O. Rousseaux, and V. Collignon. Iterative feedback tuning applied to robot joint controllers. In H.F. Chen, editor, *Proc. of the 14th IFAC World Congress*, volume I, Beijing, China, July 1999. Elsevier Science.

[30] Svante Gunnarsson and Mikael Norrlöf. Some aspects of an optimization approach to iterative learning control. In *Proc of the 38th IEEE Conference on Decision and Control*, Phoenix, AZ, USA, Dec 1999.

[31] Torkel Glad. Extensions of the rga concept to nonlinear systems. In *European Control Conference, ECC99*, page F332, Karlsrune, Germany, Sep 1999.

[32] Niclas Bergman and Fredrik Gustafsson. Three statistical batch algorithms for tracking manoeuvring targets. In *Proc. on European Control Conference ECC 99*, Karlsruhe, Germany, Aug 1999.

[33] P. Carrette and Lennart Ljung. Efficient computation of cramer-rao bounds for the transfer functions of MIMO state-space systems. In

H. F. Chen, D. Z. Cheng, and J.F. Zhang, editors, *14th World Congress of IFAC*, volume H, pages 247–252, Beijing, China, July 1999.

[34] Lennart Ljung. Estimation focus in system identification: Prefiltering, noise models, and prediction. In *IEEE Conference on Decision and Control*, Phoenix, AZ, USA, Dec 1999.

[35] Fredrik Tjärnström and Lennart Ljung. Minimizing the variance of transfer function estimates. In V.A. Yakubovich and A.L. Fradkov, editors, *6th Saint Petersburg Symposium on Adaptive Systems Theory*, volume 1, pages 194–200, S:t Petersburg, Russia, Sept 1999.

[36] Lennart Ljung. Comments on model validation as set membership identification. In A. Garulli, A. Tesi, and A. Vicino, editors, *Robusteness in Identification and Control*, volume 245 of *Lecture Notes in Control and Information Sciences*, pages 7 –17, Berlin, Sept 1999. Springer Verlag.

[37] Valur Einarsson and Torkel Glad. Verification of piecewise linear switched systems using abstractions. In *American Control Conference*, pages 2967–2971, San Diego, CA, June 1999.

[38] A. Sokolov and Torkel Glad. Identifiability of turbocharged ic engine models. In *SAE Technical Papers*, volume SP-1451, pages 1999–01–0216, Mar 1999.

[39] Torkel Glad and A. Sokolov. Structural identifiability: tools and applications. In *IEEE Conference on Decision and Control*, Phoenix, Arizona, Dec 1999.

[40] Wolfgang Reinelt, A. Garulli, Lennart Ljung, J.H. Braslavsky, and A. Vicino. Model error concepts in identification for control. In *Proc. of the 38th IEEE Conference on Decision and Control*, pages 1488–1493, Phoenix, AZ, USA, Dec 1999.

[41] Anders Helmersson. IQC synthesis based on inertia constraints. In *14th World Congress of IFAC*, volume G, pages 163–168, Beijing, China, July 1999. IFAC.

[42] Anders Helmersson. Parameter dependent lyapunov functions based on linear fractional transformation. In *14th World Congress of IFAC*, volume F, pages 537–542, Beijing, China, July 1999. IFAC.

[43] Anders Helmersson. An iqc-based stability criterion for systems with slowly varying parameters. In *14th World Congress of IFAC*, volume F, pages 525–530, Beijing, China, July 1999. IFAC.

[44] Tomas McKelvey and Anders Helmersson. A dynamical minimal parametrization of multivariable linear systems and its application to optimization and system identification. In *14th World Congress of IFAC*, volume H, pages 7–12, Beijing, China, July 1999. IFAC.

[45] Anders Stenman. Model-free predictive control. In *Preceedings of the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA*, pages 3712–3717, Dec 1999.

[46] M.W. Braun, D.E. Rivera, Anders Stenman, and W. Foslien. Comparison of global nonlinear models and model-on-demand estimation applied to identification of a rtp wafer reactor. In *Preceedings of the 38th IEEE Conference on Decision and Control, Phoenix, AZ, USA*, pages 3950–3955, Dec 1999.

[47] Måns Östring and Svante Gunnarsson. Lqg control of a flexible servo. In *Second conference on Computer Science and Systems Engineering in Linköping, CCSSE99*, pages 125–132, Oct 1999.

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Appendix I

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