LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
1998

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 Mats Jirstrand defended his Ph.D. thesis, while five of our graduate students finished their Lic. Eng. degrees: Jonas Blom, Fredrik Gunnarsson, Valur Einarsson, Mikael Norrlöf, and Per Spångéus.

In the following pages the main research results obtained during 1998 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 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.

Chapter 3

System Identification

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

A general overview of some basic concepts in system identification is given in [19].

Identification for control and iterative design techniques is a topic of considerable current interest. In [31] some some basic issues in this area are discussed.

3.1 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 parametrized state-space model. Different state-space parametrizations are discussed in [17] with an emphasis on numerical properties and convergence speed.

In [64] a fast method for numerical calculation of the prediction error gradients is presented.

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 [75].

Methods for fast calucations of linear and non-linear techniques are treated in [22].

3.2 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 [35].

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 [34] and [36] 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.

3.3 Closed-loop Identification

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

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

During 1998 we have studied some different aspects of the closed-loop identification problem which has resulted in a number of papers and reports: [13, 14, 15, 16, 27, 28, 29, 30, 85, 86]

The focus is on analyzing and devising prediction error methods for closed-loop identification. The paper [16] which will appear in Automatica during 1999 summarizes most of our efforts in this area. Another question we have studied is that of optimal experiment design, especially directed towards control applications. The papers [29, 30] contains the core results here. Other topics covered include direct identification of unstable systems using output error and Box-Jenkins models [15, 28, 85] and time-domain closed-loop identification (or even errors-in-variables identification) using periodic inputs [86].

A projection method for closed loop identification is outlined in [77].

3.4 Model on Demand

In this project we focus on the identification of nonlinear models, and, in particular, on the situation that occur when very large datasets are available.

Traditional treatments of the nonlinear identification problem 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 in this research project 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* (aka *just-in-time models*) has been adopted.

3.4.1 Time-domain Prediction

The main motivation for the model-on-demand philosophy has been the prediction problem for dynamical systems. The basic idea is to compute the fit locally within a "sliding window" $W_h(\cdot)$. That is,

$$\hat{\theta}(\varphi(t)) = \arg\min_{\theta} \sum_{k=1}^{N} \ell(y(k) - g(\varphi(k), \theta)) \cdot W_h(\|\varphi(k) - \varphi(t)\|_M), \tag{3.1a}$$

$$\hat{y}(t) = g(\varphi(t), \hat{\theta}(\varphi(t))) \tag{3.1b}$$

where $\ell(\cdot)$ is a scalar, real-valued and positive norm function, and $\|\cdot\|_M$ is a scaled distance function on the regressor space.

Since we now have to solve an optimization problem for each prediction, the parameterization $g(\cdot, \cdot)$ is usually chosen so that it is linear in the parameters, i.e., as a polynomial expansion. Then, and if a quadratic norm is used, the local estimates can be efficiently computed via weighted least squares.

However, the key issue here is how to select the weighting $W_h(\cdot)$. The standard solution, which has been extensively studied in the statistical literature, is to select the weights according to a *kernel function* parameterized by a parameter h (usually referred to as the *bandwidth*) which regulates the size of the neighborhood around $\varphi(t)$.

Methods that use the available data to produce a good bandwidth are usually referred to as *bandwidth selectors*. They can roughly be divided into "classical" methods which are based on cross-validation ideas, and "plug-in" methods which rely on asymptotic MSE expressions. The majority of the bandwidth selectors proposed so far, though, have been of global type, i.e., they produce a single global bandwidth. However, adaptive (i.e., local) methods, which select local bandwidths for each prediction, have received a lot of attention in recent years, and the development of them still seems to be an open and active research area.

In earlier contributions we have also studied an optimization approach where the the weights are optimized so as to minimize certain performance measures. It has been shown that this optimization can produce more accurate predictions for small neighborhood sizes.

3.4.2 Frequency-domain Identification

Another useful application for the model-on-demand approach is that of nonparametric *frequency response estimation* of linear and time-invariant systems. Here the objective is obtain an estimate of a system's frequency function $G(e^{i\omega})$ by smoothing the ratio of the output's and input's Fourier transforms (the so-called ETFE). Classical approaches in this context are the Blackman-Tukey procedure which forms the estimate as a ratio between cross-spectra and spectra, and Welsh's method which uses averaging of periodograms. A problem with these methods however, is that they use smoothing windows of fixed width and that this width normally has to be selected by the user by visual inspection.

In [83] we show that better performance can be achieved by allowing a frequency dependent window width which adapts to the local properties of the ETFE. The idea is to use a local estimator like (3.1) where $y(k)$ now represents the ETFE values and $\varphi(k) = \omega_k$ is the frequency. It is demonstrated how an automated procedure, based on a local bandwidth selector, leads to good choice of resolution parameter that very well matches the asymptotically optimal choice. We also present a computational procedure, based on recursive interval splitting, that drastically reduce the number of computations and the execution time.

In [21] it is shown how periodic inputs can be utilized to make the estimation process more efficient.

3.5 Analysis of Identification methods

A bias correction scheme in case of insufficiently rich excitation signals is presented in [69]

In [74] results are presented about classes of pre-filters that may result in similar model estimates by use of classical least-squares prediction error identification methods.

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 [32] to deal with parameter constraints.

Chapter 4

Nonlinear Systems

4.1 Constraints in Dynamic Systems

4.1.1 Solvability of Dynamic Systems with 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 [45] 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

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

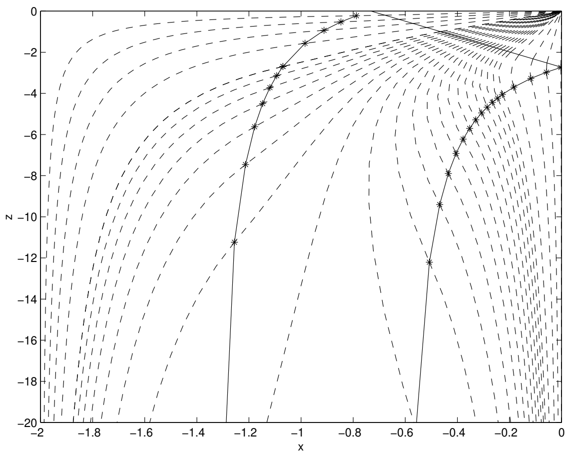
which lacks solution, since $\theta_a > 0$ and $-\theta_a > 0$ are incompatible. The original system is thus identifiable under the constraint $\theta > 0$.

4.1.2 Stabilization 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 [46]. 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 [43].

4.1.3 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 [33] 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.

4.2 Quantifier Elimination in Control

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

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

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

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

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

In [1] many of the aspects concerning the use of quantifier elimination in control are investigated. In particular it is possible to construct invariant sets for dynamic systems. The application of invariant sets to hybrid systems is discussed in [58]. Interseting possibilities come up in the use of switched control strategies. Such controllers are treated in [84] and [54]. Another type of switched controller is based on linear programming, [53], [56]. The connection with passivity is treated in [57].

4.3 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. The possibility of doing this is investigated in [44]. It is shown that 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

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

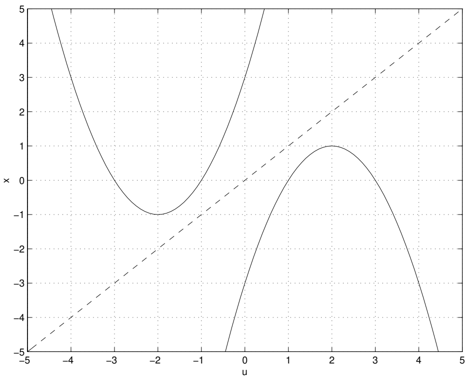


Figure 4.1: Equilibrium points of (4.2). Solid lines: asymptotically stable linearizations, dashed lines: unstable linearizations.

4.4 Robustness and Gain Scheduling using mu-methods

Stability and robustness analysis of linear systems are often handled using quadratic Lyapunov functions (LQG and H_∞). Related to this is the concept of structured singular values, or μ, which can be seen as an extension to H_∞ methods. These methods have attracted considerable interest since their introduction in 1982. The μ analysis can be seen as a refinement of the small gain theorem.

We can include knowledge about the structure of the uncertainties, which in general are linear or nonlinear operators. They are classified as (real) parametric if they are static and (complex) dynamic if they depend on previous values of its input. Controller synthesis for systems with mixed real and complex uncertainties are treated in [37].

An alternative or extension to the μ analysis is integral quadratic constraints (IQC). In this approach the uncertainties can be specified as operators satisfying an IQC. Stability of a system connected with such an uncertainty in a feedback loop can the be verified by a frequency dependent quadratic matrix inequality. Using the Kalman-Yakubovich-Popov lemma this can be converted to a pureley algebraic problem involving quadratic matrix inequalities. In [60] the synthesis problem of finding a feedback controller to such a system is treated. The result is formulated in terms of matrix inertia (the numbers of negative, zero, and positive eigenvalues).

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 joint licentiate thesis [2] about power control in mobile communication systems.

5.1 Navigation Using Terrain Elevation Databases

Consider the problem of aircraft navigation utilizing terrain information, presented in Figure 5.1. A radar altimeter measures the aircrafts ground

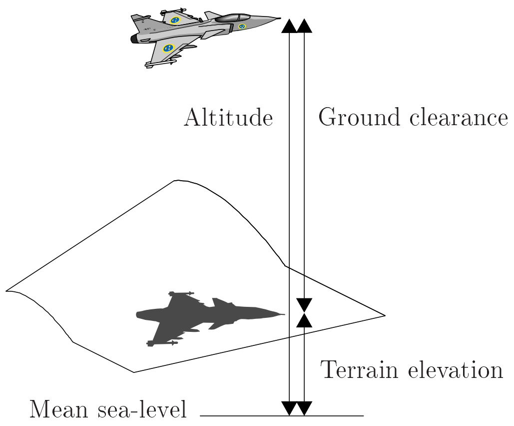


Figure 5.1: Terrain aided navigation.

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 and e_t are noises acting on the system. The unstructured information in the terrain make 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 has 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.

The results have been reported in the conference proceedings [25, 26] and the internal report [94].

5.2 Miscellaneous

During 1998 a number of resting projects were published in journal papers. For more details about these, we refer to old annual reports or the publications themselves.

- A standard problem in communication, both wireless and wirebased, is to equalize the influence of channel dynamics. The idea is to continuously adapt a model or an equalizer to the changing environment, based on an error signal. When the communication is in duplex, so called *double talk* (when both parts are talking at the same time) makes the error signal large. A standard idea is to turn off adaptation in the equalizer when double talk occurs. In [6] we propose to use change detection and diagnosis to detect and distinguish between the events double talk and echo path change. Depending on the decision (diagnosis), the adaptation is either increased or decreased.

- A related problem to the above is to parametrize the channel dynamics efficiently, allowing better performance in the estimation and equalization. In [8] we propose a structural detection scheme of the channel model which runs in parallel with the adaptive estimation algorithm.

- A Prometheus project on estimating tire-road friction for cars during 1992-1994 resulted in an invitation to Control System Magazine, [10]. The focus in the paper is on Kalman filtering and change detection, using Monte Carlo simulations for algorithm choice and optimization.

- A project on change detection in closed-loop control systems is reported in [9]. The idea is to detect changes that deteriorates performance, but to ignore other system changes. The concept was implemented and tested in real-time using a lab process DC motor.

- An interdisciplinary work on classifying bacteria using data from an artificial nose, resulted in the paper [11]. A semiphysical model was identified from the sensor time series outputs, and the parameters were used for classification. The result is that the seven classes of bacteria can be correctly classified in 90% of the cases, using cross validation.

Chapter 6

Hybrid and Discrete Systems

Here we decsribe work on hybrid and discrete systems.

6.1 Physical Modeling and Simulation of Hybrid Systems

6.1.1 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 fit 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.

6.1.2 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 mechanisms* 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.

6.1.3 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 etc.

By using the earlier introduces **Sw**-element, briefly reviewed in, e.g., [50, 78], when making physical models using bond graphs, the support from bond graph formalism is extended to hybrid systems. Bond graphs including the **Sw**-element are referred to as switched bond graph.

6.1.4 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 [50, 78]. The generation of the equations is algorithmic, and common bond graph equation generation algorithms can be used [49, 79]. The algorithms have also been verified in a singular perturbation framework [48, 87, 96]

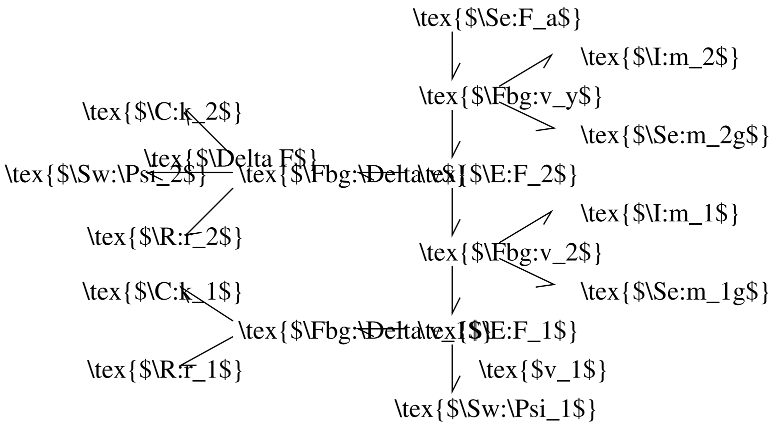


Figure 6.1: A switched bond graph model of a landing aircraft system.

A mathematical description derived from the switched bond graph in Figure 6.1 is shown in Figure 6.2 and in Table 6.1. The switched bond graph is a model of a landing aircraft system.

The continuous mode models are expressed using four state variables, where x_1 is the distance that the spring k_2 has from equilibrium and x_2 the same distance for spring k_1. x_3 is the momentum of mass m_2 and x_4 the momentum of m_1. The transition conditions in the automaton are, for each mode, replaced by an expression in the state variables.

In the landing aircraft system, all transitions but two have trivial initialization rules, and the equations for finding the initial values for the two tran-

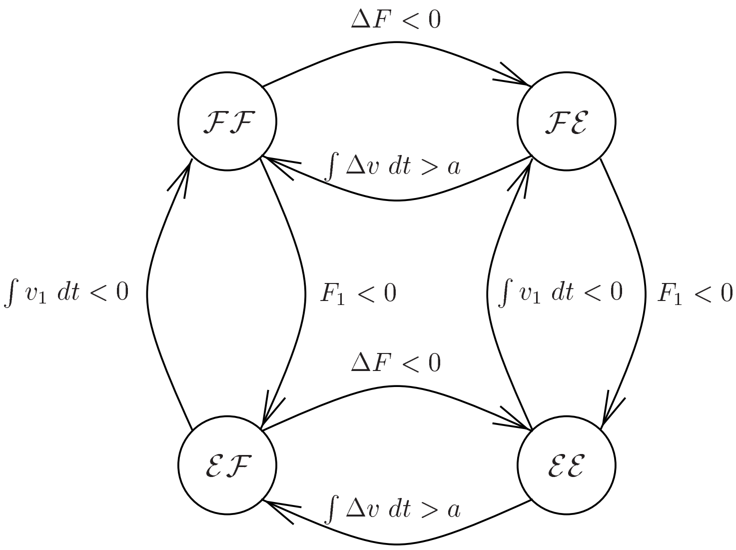


Figure 6.2: A finite automaton describing the relations between the different modes in the aircraft landing system example.

$\mathcal{FF}$

$$\dot{x}_1 = 0$$
$$\dot{x}_2 = \frac{1}{m_2} x_3$$
$$\dot{x}_3 = F_a - m_1 g - m_2 g - k_2 x_2 - \frac{r_1}{m_2} x_3 - \dot{x}_4$$
$$x_4 = \frac{m_1}{m_2} x_3$$

$\mathcal{FE}$

$$\dot{x}_1 = 0$$
$$\dot{x}_2 = -\frac{k_1}{r_1} x_2$$
$$\dot{x}_3 = F_a - m_1 g - m_2 g - \dot{x}_4$$
$$x_4 = \frac{m_1}{m_2} x_3$$

$\mathcal{EF}$

$$\dot{x}_1 = \frac{1}{m_2} x_3 - \frac{1}{m_1} x_4$$
$$\dot{x}_2 = \frac{1}{m_1} x_4$$
$$\dot{x}_3 = F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2} x_3 + \frac{r_2}{m_1} x_4$$
$$\dot{x}_4 = -m_1 g + k_2 x_1 - k_1 x_2 + \frac{r_2}{m_2} x_3 - \frac{r_1 + r_2}{m_1} x_4$$

$\mathcal{EE}$

$$\dot{x}_1 = \frac{1}{m_2} x_3 - \frac{1}{m_1} x_4$$
$$\dot{x}_2 = -\frac{k_1}{r_1} x_2$$
$$\dot{x}_3 = F_a - m_2 g - k_2 x_1 - \frac{r_2}{m_2} x_3 + \frac{r_2}{m_1} x_4$$
$$\dot{x}_4 = -m_1 g + k_2 x_1 + \frac{r_2}{m_2} x_3 - \frac{r_2}{m_1} x_4$$

Table 6.1: Equations for the four different modes in Figure 6.2.

sitions with non-trivial initializations, the ones where switch $\mathbf{Sw}:\Psi_2$ changes to state $\mathcal{F}$, are found in Table 6.2. The first equation in the table states that the velocities of the two masses should be the same when the end-stop is reached, and the last equation describes the momentum conservation. The other two state variables are continuous.

$$\frac{x_4(t)}{m_1} - \frac{x_3(t)}{m_2} = 0$$
$$x_3(t) + x_4(t) = x_3(t') + x_4(t')$$

Table 6.2: Equations giving the initial values when switch $\mathbf{Sw}:\Psi_2$ changes to state $\mathcal{F}$. $x(t')$ is the value of state x before the change of mode, and $x(t)$ the initial value of x in the new mode. x_1 and x_2 are continuous.

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 [88].

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 [89].

The singular perturbation analysis of the mode initialization procedure can also be used to prove that a certain class of bond graphs can be transformed into a state space description [90].

6.2 Diagnosis in Discrete Events 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 [47]. 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 steps:

1. The construction of a discrete event model of the system to be diagnosed, containing both the normal and faulty behavior.

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

3. Analysis of diagnosability properties of the system.

6.2.1 Modeling

Components are modeled locally in reusable component models including both normal and faulty behavior. Faults are modeled as unobservable inputs or states and represented with dedicated fault variables. The mapping from system variables to sensor readings is obtained globally and included in the relational model.

To illustrate the methods and concepts, we consider a very simple example system which is shown in figure 6.3 that 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 denoted FT (Flow Transmission). The pump and the valve can be either on/off respectively open/closed. The valve can fail in two different ways, stuck open or stuck closed.

The fault that can occur in the valve will be modeled simply as an unknown input, d, that can take the values

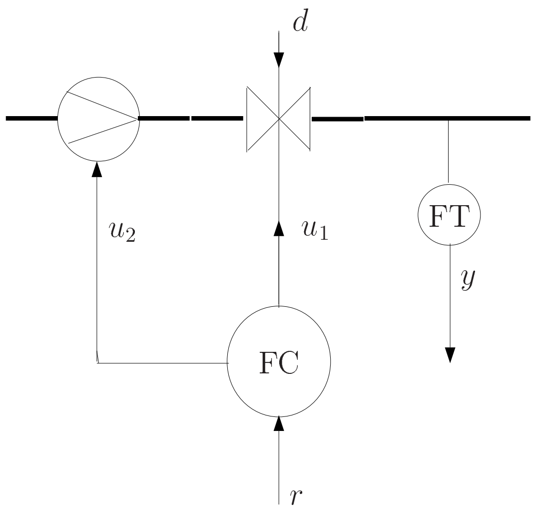


Figure 6.3: Flowchart of a simple system.

$d = 0$	The valve is stuck closed.
$d = 1$	The valve is working, i.e., responding to u_1.
$d = 2$	The valve is stuck open.

The other variables indicated in Figure 6.3 will be Boolean valued, with the obvious interpretation. For example $u_1 = \texttt{true}$ means the valve is ordered open, etc.

For the controller, we have the FSM in Figure 6.4. The sensor measures if

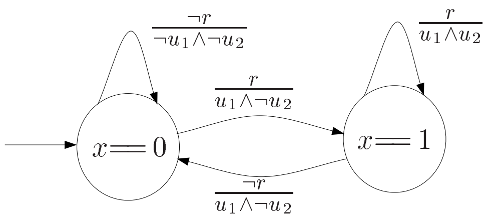


Figure 6.4: The controller.

there is flow in the pipe. The condition for the sensor output h to be `true` is that both the pump and the valve enables flow. This can be expressed as

$$y = \phi_V \wedge \phi_P$$

where

$$\phi_V(d, u_1) = (d == 1 \wedge u_1) \vee (d == 2)$$
$$\phi_P(u_2) = u_2$$

The sensor relation hence is

$$S(y, u_1, u_2, d) = (y == (\phi_V \wedge \phi_P))$$

The model of the system can then be obtained by

$$M(x, d, r, y, x^+) = \exists u_1, u_2 S(y, u_1, u_2, d) \wedge C(x, r, u_1, u_2, x^+). \quad (6.1)$$

The now internal signals u_1 and u_2 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 and the input.

6.2.2 Fault Detection and Isolation

The diagnosis problem is basically to infer the possible values of the unobservable fault inputs and states from observations of the system. Procedures for fault detection and fault isolation using the basic operations of the relational framework are presented in [47].

6.2.3 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 and the transition necessary for detection can be automatically deduced from the system model under certain conditions.

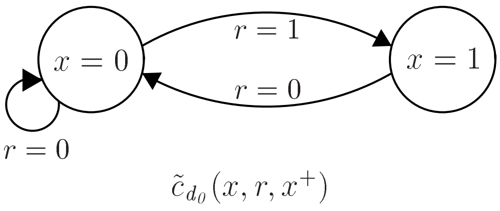
We will say that the fault detection procedure is *ambivalent with respect to* $d_{i,k}$ when the normal value $d_{i,N}$ and the fault value $d_{i,k}$ of the fault variable d_i is in the estimation set simultaneously, i.e., when the fault *and* the normal behavior is consistent with the observations.

The state and input combinations for which the fault detection procedure is ambivalent with respect to $d_{i,k}$ can be computed as

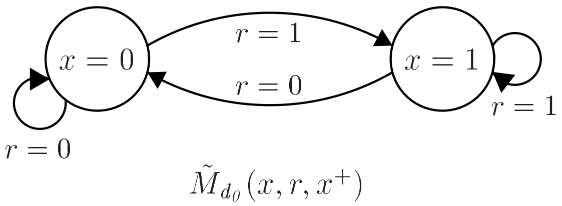
$$A_{d_{i,k}}(x, u, y) = \exists x^+, d_i^+ M_i[d_i \mapsto d_{i,N}] \wedge M_i[d_i \mapsto d_{i,k}] \quad (6.2)$$

where $A_{d_{i,k}}$ stands for ambivalent with respect to the fault $d_{i,k}$. This calculation is done under a single fault assumption.

As an example of the final result of this kind of analysis, we can look at Figure 6.5. This means that the fault valve stuck closed can only be detected



(a) The transitions for which d_0 (valve stuck closed) cannot be detected.



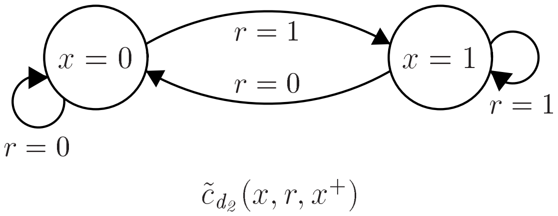
(b) The transitions possible when $d = d_N$ or $d = d_0$.

Figure 6.5: The ambivalent and possible behavior with respect to d_0 (valve stuck closed).

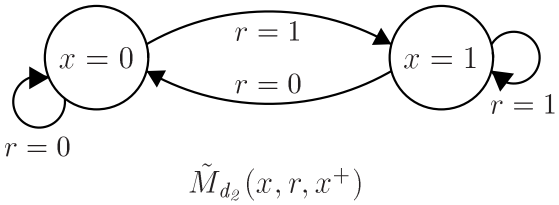
when the controller attempts to get flow through the system. This seems very reasonable. More interesting is perhaps the result for the fault valve stuck open, in Figure 6.6. Here we see that this fault is undetectable, due to the design of the controller.

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



(a) The transitions for which d_2 (valve stuck open) cannot be detected.



(b) The transitions possible when $d = d_N$ or $d = d_2$.

Figure 6.6: The ambivalent and possible behavior with respect to d_2 (valve stuck open).

Definition 6.2.1 (Isolatable faults) *For the relational model $M(x, u, y, x^+, d^+)$, we will call the two faults $d_{i,k}$ and $d_{j,l}$* isolatable *if there exists a controllable transition, i.e., values of x and u, in M which gives different behavior, i.e., outputs or next states, for the two faults. All fault variables d_s are assumed to have their normal value $d_{s,N}$ for $s \neq i, j$.*

The property in Definition 6.2.1 can be checked as follows. Calculate the two relational models $b_{d_{i,k}}$ and $b_{d_{j,l}}$.

$$b_{d_{i,k}}(x, u, y, x^+) = M_i[d_i \mapsto d_{i,k}, d_i^+ \mapsto d_{i,k}] \tag{6.3}$$

$$b_{d_{j,l}}(x, u, y, x^+) = M_j[d_j \mapsto d_{j,l}, d_j^+ \mapsto d_{j,l}] \tag{6.4}$$

The relational model $b_{d_{i,k}}(x, u, y, x^+)$ represents the behavior of the system, under the single fault assumption, if the fault $d_{i,k}$ has occured. If $b_{d_{i,k}} = b_{d_{j,l}}$, i.e., the system has exactly the same behavior for both faults, then the errors $d_{i,k}$ and $d_{j,l}$, cannot be distinguished for any input/state sequence.

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, then is given by partitioning the faults with identical behavior together.

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

$$\{\,\{\,d_{1,0},\ d_{2,0}\,\},\ \{\,d_{1,2}\,\},\ \{\,d_{2,2}\,\}\,\} \tag{6.5}$$

where it is seen that pump stuck off and valve stuck closed cannot be distinguished.

6.3 Planning using Simplified Action Structures (SAS)

Simplified action structures is a notation for finite state based systems. The states are given as tuples:

$$x = [x_1, x_2, \ldots, x_n]$$

and each x_i resides in some finite domain $\mathcal{S}_i$. The controls or inputs are termed *actions* or *operators* and their affect on the system is described through *pre-*, *post-* and *prevail-conditions*. The pre- and post-conditions tells us the actual effect of the action and the prevail-condition can detail further conditions which must be satisfied during the execution. Without further restrictions this is of course exactly the set of finite state systems.

We have focused on the *planning problem*, that is, the problem of finding a control sequence which transforms a given initial state into a desired final state. It is easy to show that without further restrictions the complexity of planning increases exponentially with the number of state variables. This is because the state space is exponential in size in terms of the number of state variables, and there are systems that force you to traverse the entire state space to reach your goal. Since a lower bound of the algorithm is derived from the size of the output it is then of course impossible to find the plan in polynomial time.

The set of problems we focus on basically excludes such processes as described above. The exact class studied is defined through explicit conditions on the actions and the structure of the transition graph for each state variable. A more thorough description can be found in [12]. The paper presents a planning algorithm that can deal with a restricted class of planning problems. The complexity of the algorithm increases polynomially with the number of actions and state variables. For example, we have modeled a simplified assembly line building Lego cars which fits into this restricted class.

6.4 Verification using Abstractions

A special class of hybrid systems are switched systems, where system trajectories are continuous but may have discontinuous derivatives. 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. This is done by obtaining discrete conservative approximations of the original system. Model checking is then applied to the abstracted system. If successful, the specification will hold for the original system. If not, we provide a counterexample.

The restriction to linear dynamics and switching surfaces facilitates use of efficient computation tools. This enables us to handle problems of interesting complexity.

Further details are presented in [3], [51] and [52].

Chapter 7

Applications

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

7.1 Cellular Radio Systems

During the last years, the market of cellular radio systems has exploded. The driving incentive is to enable communication services irrespective of time and location. As the number of users and the demand for multimedia services increase, so does the need for efficient utilization of the available resources. Extensive planning is needed during the design phase of these systems. However, some decisions have to be considered while in operation.

A consequence of the limited availability of radio channels in the network, is that the same channel has to be assigned to many users. Thus a signal intended for a certain user will reach other users, disturb their connection and thereby degrade the quality, see Figure 7.1. A user with very good quality may consider to use a lower power and still have acceptable quality. The advantage is that he will disturb other users less, and thereby their quality is improved. Power control is essentially to do the same thing but in a controlled manner.

In ideal situations, the power control problem can be solved analytically, but in real cases several aspects that tend to blur the picture have to be considered.

- In practical cases the power can only be controlled based on local mea-

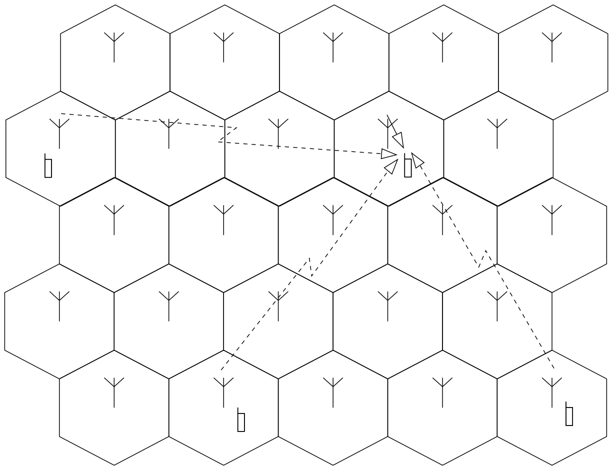


Figure 7.1: The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise.

surements 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.

- 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 thoroughly addressed in [2], where a concept of power control is proposed. Details from different perspectives are also available in [59, 41].

The dynamical effects of time delays and constraints are further discussed in [38, 39, 40, 42].

Consider a system using orthogonal channels. If the channel allocation is fixed and orthogonality is preserved despite varying signaling conditions, the situation on one channel is independent of the situation on the others. These

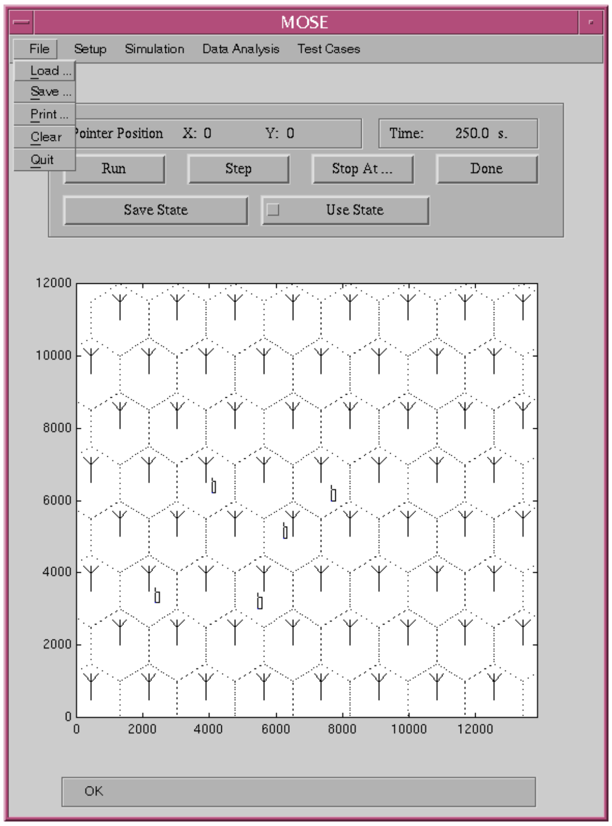


Figure 7.2: Simulation environment for power controlled mobile communication systems.

assumptions form the basis for the simulation environment presented in [82]. The cellular layout is described by a grid of hexagonal cells with equal radius. The base station antennas are omnidirectional and located in the center of the cells as seen in Figure 7.2. Analytical solutions are possible in simplified cases, but when analyzing the effects of power control subject to time delays, constraints and time-varying channels, such a tool provides valuable insight and intuition.

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

7.2 Robot Control

This project is 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. 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.

The project involves both theoretical studies and implementation. The theoretical considerations have been concentrated on convergence and robustness aspects and also the influence of load and measurement disturbances. Some results are given in [4], [71], [24]

The project has also involved development of an interface between the robot control system S4C and Matlab. This interface enables experiments and evaluations of ILC algorithms on the ABB IRB 1400 that is installed at the Division of Automatic Control, Results from these experiments are presented in [4].

7.3 Friction Estimation in Cars

In a joint project between AB Volvo and Automatic Control, Linköping University, a prototype system for estimating the friction between tire and road in vehicles has been developed. The Automatic Control group was responsible for all algorithm development, construction of hardware for a prototype and test trials. The algorithm includes Kalman filtering, change detection, outlier rejection and errors in variables compensation. A broad presentation of the problem with particular attention to change detection is given in [10].

This work has been a part of the project *Driver Assistance and Local Traffic Management* in the Swedish RTI program '91-'94. Main sponsors have been The Swedish Board for Industrial and Technical Development, AB Volvo, Saab-Scania AB and The Swedish National Road Administration.

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 and also received the Chester Carlson Prize. In 1998 he as awarded an honorary doctor's degree from Uppsala University, Uppsala, Sweden.
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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.
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Sören Hansson
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Ulla Salaneck is secretary for the control group.
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Visitors

Dr. Pierre Carrette, was a postdoctoral fellow at the Division University during April 1997 - May 1998.

Dr. Anna Lombardi, University of Siena, Siena, Italy, was visiting researcher at the Division during December 1998.

Dr. Alexander Pogromsky, St. Petersburg, Russia, was visiting researcher at the Division during October 1997 - July 1998.

Dr. Andrey Sokolov, St. Petersburg, Russia, was visiting researcher at the Division during November, 1997 - April 1999.

Y. V. Marushko, St. Petersburg, Russia, was visiting researcher at the Division during March 1998 - May 1998.

E. V. Voronina, St. Petersburg, Russia, was visiting researcher at the Division during March 1998 - May 1998.

A. Kirillov, St. Petersburg, Russia, was visiting researcher at the Division during March 1998 - May 1998.

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: Tomas McKelvey.

  Y Applied Physics and Electrical Engineering. 150 participants. Lecturer: Torkel Glad.

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

  Ie Industrial Engineering and Management, Electrical engineering variant. 90 participants. Lecturer: Tomas McKelvey.

  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. 80 participants. Lecturer: Lennart Ljung.

- *Control Theory I* (Reglerteori I) For the Industrial Engineering and Management Program. Multivariable systems, Sampled data systems, LQG-control. 25 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. 80 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. 90 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. 35 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. 120 participants. Lecturers: Tomas McKelvey et al.

- *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, 10 Participants. Lecturer: Fredrik Gustafsson.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Avaliable for several Engineering Programs. 250 Participants. Lecturer: Fredrik Gustafsson (Spring 1997) and Niclas Bergman (Fall 1997).

The computer is an important tool in control education, and all courses have computer supported problem solving sessions. In some of the courses also the exam is carried out with the computer available. A presentation of some experiences concerning computer support in control education is given in

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* (Mechanical 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

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

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

- *Fundamental Limitations in Filtering and Control* Lecturer: M. Seron and M. Braslavsky. Literature: Lecture notes.

- *Convex Optimization*. A series of seminars by the participants. Literature: Lecture notes.

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 10 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

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

Utveckling av en minsökare baserad på impulsradar. **Anders Ericsson**, FOA, Linköping, January 29, 1998.

Sliding mode approach to fuzzy gain scheduling. **Rainer Palm**, Siemens AG, February 5, 1998.

Nonlinear and Adaptive Control to Fuzzy Gain Scheduling. **Alexander Stotsky**, Royal Institute of Technology, Stockholm, February 12, 1998.

Switched Control Systems. **Karl Henrik Johansson**, Lund University, Lund, March 5, 1998.

Friction detection and compensation. **Tore Hägglund**, Lund University, Lund, March 12, 1998.

Impulse radar for detection and classification of buried land-mines. **Håkan Bruntzell**, Chalmers University of Technology, Göteborg, Sweden, March 19, 1998.

Model-based leakage detection in a fine coal injection plant. **Alexander Medvedev**, Luleå University of Technology, Luleå, March 26, 1998.

Cabin noise control in the Saab 2000 high-speed turboprop aircraft. **Urban Emborg** Saab AB, Linköping, April 1, 1998.

Grafchart and recipe-based batch control. **Karl-Erik Årzén**, Lund University, Lund, April 2, 1998.

Recent development sin MFM. **Jan Eric Larsson**, Lund University, Lund, April 16, 1998.

Neural network modelling of shock absorbers. **Mats Hedlund**, Öhlins Racing, AB, May 7, 1998.

Spatial water allocation using optimal control theory. **Per-Olof Gutman**, Israel Institute of Technology, Haifa, Israel, May 14, 1998.

Blind signal separation and direction finding of finite alphabet signals. **Mats Viberg**, Chalmers Institute of Technology, Göteborg, Sweden, June 5, 1998.

Some issus on model design. **Andreas Poncet**, ABB Corporate Research, Baden, Switzerland, August 13, 1998.

Short course on applied nonlinear and adaptive control. **Jean-Jacques Slotine**,MIT, Cambridge, MA, August 24 - 26, 1998.

Sensor management in a complex multisensor environment. **Thomas Jensen and Mathias Karlsson**, Saab Military Aerospace, Linköping, October 1, 1998.

Input-Output Approaches to H-infinity Control and Estimation **Babak Hassibi**, Information Systems Laboratory, Stanford University, Stanford, CA, October 5, 1998.

Adaptive decision support - the rough set approach. **Jan Komorowski**, Norwegian University of Science and Technology, Trondheim, Norway, October 8, 1998.

Mutually non-blocking supervisory control of discrete event systems. **Martin Fabian**, Chalmers University of Technology, Göteborg, Sweden, October 16, 1998.

Spatial processing in wireless communication systems. **Björn Ottersten**, Royal Institute of Technology, Stockholm, Sweden, October 22, 1998.

Dialects of identification and control for an optimal two degree of freedom controller. **Laszlo Keviczky**, Technical University of Budapest, Budapest, Hungary, October 30, 1998.

Intelligent engineering systems: A new paradigm for systems and control engineering. **Kishan Baheti**, National Science Foundation, Washington, DC, USA, November 2, 1998.

Multivariable control of uncertain systems with bounded inputs. **Wolfgang Reinlet**, University of Paderborn, Paderborn, Germany, November 12, 1998.

On minimum lower bounds for nonparametric regression. **Alexander Nazin**, Russian Academy of Science, Moscow, Russia, November 19, 1998.

Applied optimization research of Mälardelens Högskola. **Kenneth Holmström**, Mälardalens Högskola, Västerås, Sweden, December 3, 1998.

Appendix E

Travel and Conferences

Niclas Bergman participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10. July 6-10 he participated in the FUSION'98 Conference in Las Vegas, USA. He took part in the ERNSI Workshop on System Identification in Vienna, Austria, September 27-30. He was a guest researcher at the Signal Processing Group at Cambridge University, Cambridge, UK, October 25 - November 6. December 15-18 he participated in the IEEE Conference on Decision and Control in Tampa, FL, USA.

Jonas Blom participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10. In June he took part in ICT'98, Chalkidiki, Greece. He visited the Department of Electrical Engineering at University of Newcastle, Australia November 7, and the Telecommunications Engineering Group at Australian National University, Canberra, Australia, November 13. During November 8-12 he participated in GLOBECOM'98, Sydney, Australia.

Krister Edström took part in the IMACS Multiconference on Computational Engineering in System Applications in Nabeul-Hammamet, Tunisia, April 1-4. He participated in the French-Swedish Control meeting in Lund, Sweden on April 22-24 and in Reglermöte '98 in Lund, Sweden on June 10-12. And December 15-18 he participated in the IEEE Conference on Decision and Control in Tampa, FL, USA.

Valur Einarsson participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10. He took part in the French-Swedish Control meeting in Lund, Sweden on April 22-24 and in Reglermöte '98 in Lund, Sweden on June 10-12. October 19-21 he participated in the KIT Workshop on Verification of Hybrid Systems in Grenoble, France. And December 15-18 he participated in the IEEE Conference on Decision and Control in Tampa, FL, USA.

Torkel Glad took part in the French-Swedish Control meeting in Lund on April 22-24 and in the Third Russian-Swedish Control Conference in Stockholm on May 11-13. He also took part in Reglermöte 98 in Lund on June 10-12, the NOLCOS'98 conference in Enschede, the Netherlands on July 1-3 and the MTNS'98 conference in Padova, Italy on July 6-10.

Fredrik Gunnarsson participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10. In June he took part in Reglermöte'98, Lund, Sweden. He visited the Department of Electrical Engineering at University of Newcastle, Australia November 3-7, and the Telecommunications Engineering Group at Australian National University, Canberra, Australia, November 13. During November 8-12 he participated in GLOBECOM'98, Sydney, Australia.

Svante Gunnarsson participated in Reglermöte'98, Lund, Sweden June 1998.

Fredrik Gustafsson participated in Reglermöte'98, Lund, Sweden, June 1998. During December 15-18 he participated in CDC, Tampa, Florida. September 26-27, he participated in NUTEK's telecom meeting, Gothenburg. He participated in a workshop on non-stationary signal processing organized by the Isaac Newton Institute, Cambridge, July 6-10.

Anna Hagenblad participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10 and in Reglermöte '98, Lund, Sweden, June 10-12. She also took part in the ERNSI Workshop on System Identification in Vienna, Austria, September 27-30 and the 37th IEEE Conference on Decision and Control in Tampa, FL, USA in December.

Kent Hartman Participated in "Examination i Högskolan" in Uppsala, Sweden, March 31, Reglermöte'98, June, Lund, Sweden. He also particpated in UNISCENE (University Network for Innovative Student-Centred Education), University of Twente, Nederländerna, June 15 -16.

Inger Klein participated in Reglermöte'98, Lund, Sweden, June 1998.

Lennart Ljung participated in the Workshop on Learning, Intelligence and Hybrid Systems, Bangalore, India January 5 - 12, 1998 March 9-10 he participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, and April 23 - 25 he participated in the Trident Symposium, Lund. May 11-13 he took part in the Third Swedish Russian Control Meeting in Stockholm. May 19 -20 he participated in the ABB

Control Workshop in Västerås. June 10 -12 Lennart Ljung participated in Reglermöte'98, Lund, Sweden and 29 - July 1 in the conference "Perspectives in Control" in Paris, France. July 29 - August 1 he took part in the meeting Robust Identification and Control, in Sienna, Italy. August 31-September 2 he lectured at the Summer Course on "Interaction between Identification and Control Design" in Grenoble, France. September 28 - 29 Lennart Ljung participated in the European Network ERNSI Annual Meeting on System Identification. On October 23 he was the faculty opponent on the thesis by Henrik Sahlin at Chalmers University in Göteborg, Sweden. November 27 - December 1 he visited Hong Kong University of Science and Technology. December 15 - 18 he took part in the 37th IEEE Conference on Decision and Control in Tampa, FL, USA

Mikael Norrlöf participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10, the IEEE International Conference on Robotics and Automation (ICRA'98), Leuven, Belgium, May 1998, and Reglermöte'98, Lund, Sweden, June 1998. He also took part in the NUTEK Competence Center Day, October 20, 1998, Lund, Sweden.

Ulla Salaneck participated in Reglermöte'98, Lund Sweden, June 1998.

Anders Stenman was a guest researcher at the Control Systems Engineering Laboratory at Arizona State University, Tempe, USA, August 28 - October 2, 1998.

Fredrik Tjärnström participated in the Conference on Computer Science and Systems Engineering in Norrköping, Sweden, March 9-10, in Reglermöte '98, Lund, Sweden, June 10-12, and in the ERNSI Workshop on System Identification in Vienna, Austria, September 27-30.

Appendix F

Lectures by the Staff

Niclas Bergman: *C-R bound and PMF for terrain aided navigation*, S3 Royal Institute of Technology (KTH), Stockholm, Sweden, February 2, 1998.

Niclas Bergman: *Matlabkursen*, IT-dygnet, Linköping, Sweden, April 24, 1998.

Niclas Bergman: *Sensordatafusion*, Saab AB, Linköping, Sweden, May 7, 1998.

Niclas Bergman: *Sensordatafusion och terrängnavigering*, The ISIS Workshop on Sensor Fusion, Linköping, Sweden, May 28, 1998.

Niclas Bergman: *Bayesian Terrain Navigation using numerical integration*, Cambridge University, Cambridge, UK, November 3, 1998.

Jonas Blom: *Constrained Power Control Subject to Time Delays*, ICT'98, Chalkidiki, Greece, June 23.

Jonas Blom: *A New Concept of Power Control in Cellular Systems Reflecting Challenges of Today's Systems*, GLOBECOM'98, Sydney, Australia, November 10.

Jonas Blom: *Estimation in Cellular Radio Systems*, Australian National University, Canberra, Australia, November 13.

Valur Einarsson: *Verification of piecewise linear switched systems using abstractions*, Swedish-French control meeting, Lund, Sweden, April 24, 1998.

Valur Einarsson *Methods for verification of piecewise linear systems*, Conference on Computer Science and Systems Engineering, Norrköping, Sweden, March 10, 1998.

Torkel Glad: *Switched systems generated by optimality criteria*, Swedish-French control meeting, Lund, April 24.

Torkel Glad: *Moving between the equilibria of a nonlinear system*, Swedish-

Russian Control conference, Stockholm, May 12.

Torkel Glad: *Identifiability with constraints*, NOLCOS'98, Enschede, the Netherlands, July 2.

Torkel Glad: *Moving the state between equilibria*, NOLCOS'98, Enschede, the Netherlands, July 3.

Torkel Glad: *Analysis of actuator cross coupling in aircraft*, MTNS'98, Padova, Italy, July 8.

Fredrik Gunnarsson: *Constrained Power Control in Cellular Systems Subject to Time Delays*, Reglermöte'98, Lund, Sweden, June 11.

Fredrik Gunnarsson: *Power Control in Cellular Radio Systems*, University of Newcastle, Australia, November 4.

Fredrik Gunnarsson: *Power Control in Cellular Systems Subject to Constraints and Time Delays*, GLOBECOM'98, Sydney, Australia, November 11.

Fredrik Gunnarsson: *Estimation in Cellular Radio Systems*, Australian National University, Canberra, Australia, November 13.

Fredrik Gustafsson: *Automotive applications on adaptive filtering and change*, Isaac Newton Institute, Cambridge, UK, July 21, 1998.

Fredrik Gustafsson: *MDL as a performance measure for choosing adaptive filters*, Isaac Newton Institute, Cambridge, UK, July 23, 1998.

Fredrik Gustafsson: *Utilizing periodic excitation in prediction error based system identification*, CDC, Tampa, December, 1998.

Lennart Ljung: *Identification for Control: What is There to Learn* Workshop on Learning, Intelligence and Hybrid Systems, Bangalore, India, January 6, 1998.

Lennart Ljung: *An overview of the control research in Linköping*, the Trident Symposium, Lund, Sweden, April 24, 1998.

Lennart Ljung: *Closed Loop Identification Revisited*, Third Swedish-Russian Control Meeting, Stockholm, Sweden. May 12, 1998.

Lennart Ljung: *From Data to Model - A survey of System Identification*, ABB Control Workshop, Västerås, Sweden May 19, 1998.

Lennart Ljung: *Bias, Variance and Optimal Experiment Design: Some Comments on Closed Loop Identification*, Perspectives in Control, Paris, France, June 30, 1998.

Lennart Ljung: *A Robust Projection Method for Identifying Systems Operating in Closed Loop*, "Robust Identification and Control Meeting, Sienna, Italy, July 31, 1998.

Lennart Ljung: *Identification in Open Loop and Evaluation of Model Qual-*

ity, Summer Course on Interaction between Identification and Control Design, Grenoble, France, September 1, 1998.

Lennart Ljung: *Time and Frequency Domain Methods* ERNSI meeting, Vienna, Austria, September 29, 1998

Lennart Ljung: *Identification and Model Validation for Control Applications*, Hong Kong, November 30, 1998.

Lennart Ljung: *Identification of Unstable Systems Using Output Error and Box-Jenkins Model Structures*, 37th IEEE CDC, Tampa, FL., December 16, 1998.

Lennart Ljung: *Identification for Control - Some Results on Optimal Experiment Design*, 37th IEEE CDC, Tampa, FL., December 17, 1998.

Tomas McKelvey:*Dynamic minimal parametrizations of multivariable linear systems*, Chalmers University of Technology, Sweden, June 17, 1998.

Tomas McKelvey: *Laboteket – Ett laborationskoncept mot ett ökat studentansvar för lärandet*, NyIng Högskolekonferens 1998, Linköping, Sweden, October 19, 1998. Mikael Norrlöf: *On Analysis and Implementation of Iterative Learning Control*, ABB Robotics Products, Västerås, Sweden, December 9, 1998.

Anders Stenman: *Model on Demand*, Arizona State University,Tempe, Arizona, September 4, 1998.

Appendix G

Publications

Ph.D. Theses

[1] M. Jirstrand. *Constructive Methods for Inequality Constraints in Control*. PhD thesis, Department of Electrical Engineering, Linköpings universitet, May 1998.

Licentiate Theses

[2] J. Blom and F. Gunnarsson. Power control in cellular radio systems. Licentiate thesis LIU-TEK-LIC-1998:41 Linköping Studies in Science and Technology. Thesis No 706, Department of Electrical Engineering, Linköpings universitet, June 1998.

[3] V. Einarsson. On verification of switched systems using abstractions. Licentiate thesis LIU-TEK-LIC-1998:40 Linköping Studies in Science and Technology. Thesis No 705, Department of Electrical Engineering, Linköpings universitet, June 1998.

[4] M. Norrlöf. On analysis and implementation of iterative learning contol. Licentiate thesis LIU-TEK-LIC-1998:62 Linköping Studies in Science and Technology. Thesis No 727, Department of Electrical Engineering, Linköpings universitet, October 1998.

[5] P. Spångéus. Hybrid control using LP and LMI methods - some applications. Licentiate thesis LIU-TEK-LIC-1998:59 Linköping Studies in Science and Technology. Thesis No 724, Department of Electrical Engineering, Linköpings universitet, October 1998.

Journal Papers and Book Chapters

[6] C. Carlemalm and F. Gustafsson. On detection and discrimination of double talk and echo path changes in a telephone channel. In A. Prochazka, J. Uhlir, P.J.W. Rayner, and N.G. Kingsbury, editors, *SIGNAL ANALYSIS AND PREDICTION*, Applied and Numerical Harmonic Analysis. Birkhauser Boston, 1998.

[7] S. T. Glad and M. Jirstrand. Using differential and real algebra in control. In N. Munro, editor, *The Use of Symbolic Methods in Control System Analysis and Design*, IEE Control Engineering Series. IEE, 1998.

[8] J.Homer, I.Mareels, R.Bitmead, B.Wahlberg, and F.Gustafsson. LMS estimation of sparsely parametrized channels via structural detection. *IEEE Trans. on Signal Processing*, 46(10):2651–2663, 1998.

[9] F. Gustafsson and S. F. Graebe. Closed loop performance monitoring in the presence of system changes and disturbances. *Automatica*, 34(11):1311–1326, 1998.

[10] F. Gustafsson. Estimation and change detection of tire - road friction using the wheel slip. *IEEE Control System Magazine*, 18(4):42–49, 1998.

[11] M.Holmberg, F. Gustafsson, E.G. Hörnsten, F.Winquist, L.E. Nilsson, L.Ljung, and I.Lundström. Feature extraction from sensor data on bacterial growth. *Biotechnology techniques 12 (4): 319-324, April 1998*, 12(4):319–324, 1998.

[12] I. Klein, P. Jonsson, and C. Bäckström. Efficient planning for a miniature assembly line. *Artificial Intelligence in Engineering*, 13(1):69–81, September 1998.

[13] L. Ljung and U. Forssell. An alternative motivation for the indirect approach to closed-loop identification. *IEEE Transactions on Automatic Control*, to appear. Preliminary version available as Technical Report LiTH-ISY-R-1989, Linköping University, Linköping, Sweden.

[14] U. Forssell and L. Ljung. A projection method for closed-loop identification. *IEEE Transactions on Automatic Control*, to appear. Preliminary version available as Technical Report LiTH-ISY-R-1984, Linköping University, Linköping, Sweden.

[15] U. Forssell and L. Ljung. Identification of unstable systems using output error and Box-Jenkins model structures. *IEEE Transactions on Automatic Control*, to appear.

[16] U. Forssell and L. Ljung. Closed-loop identification revisited. *Automatica*, to appear. Preliminary version available as Technical Report LiTH-ISY-R-2021, Linköping University, Linköping, Sweden.

[17] T. McKelvey. Discussion: 'On the use of minimal parametrizations in multivariable ARMAX identification' by R.P. Guidorzi. *European Journal of Control*, 4:93–98, 1998.

[18] H. Hjalmarsson, M. Gevers, S. Gunnarsson, and O. Lequin. Iterative feedback tuning: Theory and applications. *IEEE Control Systems*, 18:26–41, 1998.

[19] Lennart Ljung. System identification. In A. Prochazka, J Uhlir, P.J.W. Rayner, and N.G. Kingsbury, editors, *Signal Analysis and Prediction*, Applied and Numerical Harmonic Analysis, chapter 11, pages 163–174. Birkh"auser, Boston, 1998.

Conference Papers

[20] C. Carlemalm and F. Gustafsson. MAP based shcemes for detection of double talk and abrupt changes in the exho path for rading channels. In *Proc. of the IVth EUSIPCO*, Rhodos, Greece, 1998.

[21] F. Gustafsson and J. Schoukens. Utilizing periodic excitation in prediction error based system identification. In *CDC'98, Orlando, USA*, 1998.

[22] J. Schoukens, Y. Rolain, F.Gustafsson, and R.Pintelon. Fast calculations of linear and nonlinear least-squares estimates for system identification. In *CDC'98, Orlando, USA*, 1998.

[23] J. Gunnarssson, T. McKelvey, and A. Helmersson. Matrix algebra package for mathematica. In *Reglermöte '98*, pages 84–87, June 1998.

[24] M. Norrlöf and S. Gunnarsson. On iterative learning control with disturbances. In *Reglermöte'98*, pages 198–202, June 1998.

[25] N. Bergman. An interpolating wavelet filter for terrain navigation. In *Proc. conf. on multisource-multisensor information fusion*, pages 251–258, 1998.

[26] N. Bergman. Deterministic and stochastic Bayesian methods in terrain navigation. In *Proc. 37:th IEEE Conf. on Decision and Control*, 1998.

[27] U. Forssell and C. T. Chou. Efficiency of prediction error and instrumental variable methods for closed-loop identification. In *Proceedings of the 37th IEEE Conference on Decision and Control*, pages 1287–1288, Tampa, FL, 1998.

[28] U. Forssell and L. Ljung. Identification of unstable systems using output error and Box-Jenkins model structures. In *Proceedings of the 37th IEEE Conference on Decision and Control*, pages 3932–3927, Tampa, FL, 1998.

[29] U. Forssell and L. Ljung. Identification for control: Some results on optimal experiment design. In *Proceedings of the 37th IEEE Conference on Decision and Control*, pages 3384–3389, Tampa, FL, 1998.

[30] L.Ljung and U. Forssell. Bias, variance and optimal experiment design: Some comments on closed loop identification. In *Proc. Colloquim on Control Problems in Honor of Prof. I.D. Landau*, Paris, June 1998. Springer Verlag.

[31] Lennart Ljung. Identification for control – what is there to learn? In Y. Yamamoto and S. Hara, editors, *Learning, Control and Hybrid Systems*, volume 241 of *Springer Lecture Notes in Control and Information Sciences*, pages 207–221, Berlin, Dec 1998. Springer Verlag.

[32] Torkel Glad and Lennart Ljung. Identifiability with constraints. In *NOLCOS 1998*, pages 455–458, Enschede, the Netherlands, July 1998. NOLCOS.

[33] Torkel Glad and A. J. Isaksson. Bounds on the response time under control constraints. In *Proceedings 37th CDC, Tampa, Fa, USA*, pages 929–930, Dec 1998.

[34] A. Hagenblad. Identifiering av Wienermodeller. In *Proc. Reglermöte*, Lund, Sweden, June 1998.

[35] Anna Hagenblad. Identification of wiener models. In *First Conference on Computer Science and Systems Engineering in Linköping*, volume 1, pages 175–183. ECSEL, Jan 1998.

[36] A. Hagenblad and L. Ljung. Maximum likelihood identification of wiener models with a linear regression initialization. In *Proc. 37:th IEEE Conf. on Decision and Control*, Tampa, FL, USA, December 1998.

[37] Anders Helmersson. μ Synthesis and LFT Gain Scheduling with Real Uncertainties. *International Journal of Robust and Nonlinear Control*, 8:631–642, 1998.

[38] J. Blom, F. Gunnarsson, and F. Gustafsson. Constrained power control subject to time delays. In *Proc. International Conference on Telecommunications*, Chalkidiki, Greece, June 1998.

[39] F. Gunnarsson, J. Blom, and F. Gustafsson. Constrained power control in cellular systems subject to time delays. In *Proc. Reglermöte*, Lund, Sweden, June 1998.

[40] F. Gunnarsson, J. Blom, and F. Gustafsson. Power control in cellular systems subject to constraints and time delays. In *Proc. IEEE Global Telecommunications Conference*, Sydney, Australia, November 1998.

[41] J. Blom, F. Gunnarsson, and F. Gustafsson. A new concept of power control in cellular systems reflecting challenges of today's systems. In *Proc. IEEE Global Telecommunications Conference*, Sydney, Australia, November 1998.

[42] F. Gunnarsson, J. Blom, and F. Gustafsson. Power control algorithms and stability analysis for radio network control. In *Proc. IEEE Conference on Decision and Control*, Tampa, FL, USA, December 1998.

[43] S. T. Glad. Switched systems generated by optimality criteria. Lund, Sweden, 1998. Swedish-French Control Meeting.

[44] M. Jirstrand and S.T. Glad. Moving the state between equilibria. pages 836–841, Enschede, the Netherlands, 1998. NOLCOS'98.

[45] S. T. Glad and L. Ljung. Identifiability with constraints. pages 455–458, Enschede, the Netherlands, 1998. NOLCOS'98.

[46] S. T. Glad. Analysis of actuator cross coupling in aircraft. Padova, Italy, 1998. MTNS'98.

[47] M. Larsson. Diagnosis and analysis of diagnosis properties using discrete event dynamic systems. In *Proceedings of the 37th IEEE Conference on Decision and Control (CDC)*, pages 3775–3780, Tampa, Florida USA, December 1998. IEEE.

[48] K. Edström. Singular perturbation analysis of a mode initialization algorithm for simulating mode switching system. In *Proceedings of the 37th IEEE Conference on Decision and Control (CDC)*, Tampa, Florida USA, December 1998. IEEE.

[49] K. Edström. Mode initialization when simulating switched bond graphs. In *Proceedings of the IMACS Muliconference on Computational Engineering in System Applications (CESA)*. IMACS, April 1998.

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[53] M. Jirstrand and P. Spångéus. A linear programming approach to the design of thermostat controllers of interconnected thermal systems. In *Proceedings of CCSSE98*, pages 47–54, March 1998.

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