Contents

Chapter 1

Introduction

The Division of Automatic Control at Linköping University consists of some twenty-five people. We teach thirteen undergraduate courses to more than one thousand 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 three areas

- Nonlinear Modelling and Control
- "Conventional" System Identification and Signal Processing (including Adaptive Control)
- "Non-conventional" System Identification and Signal Processing

The third item represents an emerging interest in problems of how to deal with information of discrete and symbolic character in our conventional model world of differential/difference equations and stationary stochastic processes.

In the following pages the main research results obtained during the academic year 1990/91 are summarized. More details about the results can be found in the listed articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items in these appendices). These reports are available free of charge.

Main events during the year include that Fredrik Gustafsson, Håkan Hjalmarsson, Sören Andersson and Ke Wang Chen completed their licentiates' theses.

Chapter 2

Reglermöte 90

October 24-25, the control group organized a Swedish Automatic Control Conference: **Reglermöte 90**. Such a meeting has been organized every second year in the 80's by different Swedish groups. The purpose is to bring together control engineers in Swedish industry and researchers and Ph.D. students at the Swedish academic institutions. Reglermöte 90 had some 200 participants, about half of them from industry. 46 papers were presented over the two days, including several poster presentations. Also half of these contributions came from industry.

The plenary addresses included a presentation by Per Olof Elgcrona, SAAB-SCANIA, who described the control system in the new Swedish military aircraft JAS-Gripen - one of the most advanced control applications in Sweden. Moreover, Lennart Haglund, Stora Teknik, described the *actual* industrial needs in the control area and presented what should be the process industry's demands on the researchers in automatic control. This spurred considerable interest.

The meeting also include hardware and software demonstrations by manufacturers.

Chapter 3

System Identification

System identification concerns the problem of estimating mathematical models of dynamical systems from observed input-output data. Within this general area several research problems have been investigated. These are described below.

3.1 Model Quality: The Roles of Prior Knowledge and Data Information

A model is useless without an estimate of its reliability. Any modeling, estimation or identification procedure must therefore be accompanied by a method to assess the accuracy of the delivered model. One could even say that the product delivered to the user must be a set of models, among which a useful or "true" description is (likely) to be found. If the objective is to design a regulator, it is actually the delivered set that is the input to the (robust) control synthesis. Recently, there has been a lively discussion around these issues in the control community. Spurred by criticism from the "robust control community" that the traditionally delivered model sets are not fit for reliable control design, many different activities have followed. We have studied how undermodelling can be viewed as bounded noise. Hence, tools from set membership identification can be used to derive transfer function error bounds. This idea is developed in [32] and [65].

The effects of undermodelling in fault detection is studied in [37].

When using parametric models it is of importance to assess the quality of a model obtained from a finite data record relative to the optimal one (in the mean square sense) within the chosen model structure. The error stems from random variations in the measurements and from the unmodelled dynamics. It can be measured in terms of the parameter uncertainty. Traditional methods to estimate this *random error* are based on the assumption that the model structure includes the true system. In [87], [2] and [98] a method is given that is consistent even in the case of under-modeling. Here, the close connection between the variability of recursive estimates with exponential forgetting and ordinary least squares estimates is explored.

Furthermore in [2] ist is discussed how to cope with identifying a system that is inherently ill-defined, so as to come up with conficence description that will not tend to a single model even as the number of observations tend to infinity.

3.2 Black-Box Modelling using Prior Knowledge

Finite impulse response (FIR) models are commonly used to describe stable transfer functions. The reason is that robust linear regression techniques can be applied to estimate FIR models. Given a stable transfer function $G(q)$, a FIR approximation can be obtained by truncating the power series expansion of $G(z)$,

$$G(z) \approx \sum_{k=1}^{n} g_k z^{-k}. \tag{3.1}$$

However, to be able to obtain useful approximation of resonant systems and/or continuous time systems sampled with a sampling rate suitable for control, the order n may have to be taken very large. The problem is that the delay operator q^{-1} has a too short memory. By the following change of basis functions we obtain much better low order approximations:

1. Laguerre functions:

$$z^{-k} \to L_k(z,a), \quad L_k(z,a) = \frac{\sqrt{1-a^2}}{z-a}\left[\frac{1-az}{z-a}\right]^{k-1}, \; -1 < a < 1,$$

2. Kautz functions:

$$z^{-k} \to \Psi_k(z,b,c),$$

$$\Psi_{2j-1}(z,b,c) = \frac{\sqrt{1-c^2}(z-b)}{z^2+b(c-1)z-c}\left[\frac{-cz^2+b(c-1)z+1}{z^2+b(c-1)z-c}\right]^{j-1},$$

$$\Psi_{2j}(z,b,c) = \frac{\sqrt{(1-c^2)(1-b^2)}}{z^2+b(c-1)z-c}\left[\frac{-cz^2+b(c-1)z+1}{z^2+b(c-1)z-c}\right]^{j-1},$$

$$-1 < b < 1, \qquad -1 < c < 1$$

By appropriate choices of a or b, c (based on *a priori* knowledge) the use of the above transformations corresponds to representing the transfer function around a time constant reflecting the behaviour of the system to be estimated. Many results from the established black-box system identification theory have been generalized to Laguerre/Kautz models:

1. Laguerre transfer function estimates are analyzed in detail in [17]. Consistency (error bounds), persistence of excitation and asymptotic statistical properties are investigated.

2. Frequency domain description of the tracking ability and disturbance rejection trade-off in recursive identification of Laguerre models is studied in [27].

3. To be able to handle resonant systems Kautz functions are introduced in [39], i.e., by using operators with complex poles more adequate descriptions of poorly damped systems are obtained.

4. A package of MATLAB m-files for identification of Laguerre/Kautz models compatible with System Identification ToolBox has been developed, and is available on request.

3.3 Parameter Identifiability

A long standing problem in System Identification is that of parameter identifiability. This concerns the question whether it is possible to uniquely (globally!) determine the values of model parameters from input-output data. Solutions have existed for certain traditional linear black-box structures. Howpever the general problem is known to be "difficult".

In [19, 29], using tools from differential algebra, we have given a constructive approach to this problem. Briefly, global parameter identifiability has been shown to be equivalent to the possibility to rearrange the original model equation to a linear regression (in the original parameters!). A constructive test which converges in a finite number of steps has been developed and implemented in Macsyma.

Chapter 4

Tracking

4.1 General Aspects

Consider the problem to track a time varying parameter vector $\theta(t)$ in a linear regression model

$$y(t) = \varphi^T(t)\theta(t) + e(t) \tag{4.1}$$

based on measurements of $\{y(t)\}$ and $\{\varphi(t)\}$. There is quite a substantial literature dealing with algorithms and analysis of this problem. A basic algorithm is the following one

$$\hat{\theta}(t) = \hat{\theta}(t-1) + P(t)\varphi(t)(y(t) - \varphi^T(t)\hat{\theta}(t-1)) \tag{4.2}$$

The many algorithms differ primarily in the choice of $P(t)$. This in turn can be interpreted as introducing various assumptions about the variation of the true parameter $\theta(t)$. A survey over approaches to the tracking problem and analysis of tracking properties is given in [76].

An analysis result on the tracking error is developed in [80, 84]. It has the basic form

$$\mid \Pi(t) - \hat{\Pi}(t) \mid \leq \sigma(\mu) \cdot \mu \tag{4.3}$$

where μ is the step size in (4.2), $\Pi(t)$ is the true tracking error

$$\Pi(t) = E(\theta(t) - \hat{\theta}(t))(\theta(t) - \hat{\theta}(t))^T$$

and $\hat{\Pi}(t)$ is the conventional, asymptotic (in $\mu \to 0$) estimate of this variance. Moreover, $\sigma(\mu)$ is a function that tends to zero as μ tends to zero.

Unlike most previous results, (4.3) is not, in itself, asymptotic in $\mu \to 0$. It applies over unbounded time intervals and also to the transient phase of the tracking.

4.2 Segmentation

In this work the problem of abrupt changes in the dynamical properties of signals and systems is studied. The goal is to estimate the time instants when these changes occur in a statistical optimal way. The proposed method is model based. The measured signal y_t is described as a linear regression,

$$y_t = \varphi_t^T \theta_t + e_t.$$

The unique feature in segmentation is that the time-varying parameter vector is assumed to be piecewise constant, in contrast to tracking problems where it is commonly modelled as a random walk. The estimate of the change instants in θ_t is found by maximizing the *maximum a posteriori* (MAP) probability or, alternatively, the likelihoods.

The basic idea is that the parameters can either change or not change at each time instant. With t measurements there are 2^t possibilities and each *a posteriori* probability has to be considered. The inevitable problem is that each one requires one filter, and this exponential growth make a direct implementation impossible. Fortunately, some relations between the *a posteriori* probabilities have been found, so only a small number of sequences really has to be considered. This number is between 2 and t dependent on the noise e_t. A remarkeble result is that the lower bound of just two filters is achievable if the noise magnitude is small enough. The details are given in [1] and [31].

One example of segmentation is the following. Consider a vehicle moving along the path in Figure 4.1, which is sampled from a city map. This signal can be modelled by piecewise straight lines, so the parameter vector consists of velocities in two dimensions. The segmentation problem is to estimate the time instants for the turns of the vehicle and in this way be able to track and predict its movements. The classical approach is to use an adaptive filter, for

Figure 4.1: A sampled path and the estimated jump instants (*).

instance RLS with forgetting factor, but it will give a long transient response after each turn. The aforementioned optimal estimates for this example are shown in the figure as stars. The smoothed parameter estimates is not shown in the figure, but can they can easily be reconstructed by drawing straight lines between the stars. As seen, every turn is found and the roundabout is approximated well. For this example, with 117 measurements, the computation of the MAP estimate requires only 17 filters. This is a considerable decrease compared to 2^{117}!

An on-line implementation requires an *a priori* fixed number of filters. A discussion is given in [1] on different search strategies, which use an *a priori* known constant number of filters to get a natural appoximation of the MAP estimate.

4.3 Model quality in recursive identification of time varying systems

A fundamental problem in recursive identification of systems and signals with time varying properties is the trade off between tracking capability and disturbance rejection. This problem has been studied by deriving expressions for the mean square error (MSE) of the estimated transfer function, under the assumptions that the variations of the system are slow, that the model is updated slowly and that the model order is high. The MSE expressions explicitly show how, for example, the design variables, the input and disturbance signals and the model order affect the model quality.

Three recursive identification algorithms have been studied: the least mean squares (LMS) algorithm, the recursive least squares (RLS) algorithm and a Kalman filter like identification algorithm. The algorithms have been applied to systems that can be described by linear regressions. Different model structures can be obtained by different choices of elements in the regression vector. We have for example studied the use of Laguerre filters, by which the model order needed to give a desired accuracy can be reduced. This approach is presented in [27].

How to relax the positive real condition in the extended least-squared scheme is studied in [36] and [6].

Chapter 5

Sensor Array Processing

Sensor array processing (SAP) has been an active research area for more than 20 years. The automatic control group has performed work in this field the last five years. The projects reported in the Sections 5.1 and 5.2 have been initiated in cooperation with the Information Systems Laboratory at Stanford University, Stanford, USA. The project of Section 5.3 has been guided by discussions with the Radio Research Department at Ericsson Radio Systems AB.

In this context, a *sensor array* consists of a group of spatially distributed sensors. Arrays of electromagnetic antennas are frequently encountered in communication and radar applications, when the signal transmission is subject to undesired interference. Acoustic devices (hydrophones) are used in, e.g., underwater and seismic applications. Impinging on the array are the superimposed waveforms of several signal sources. The problem is to detect and locate these emitters and/or to separate the individual signal waveforms.

Let an array of m sensors receive the wavefronts of d emitters, where $d < m$. The sensor outputs are sampled and collected in a vector $\mathbf{x}(t)$, modeled by the equation

$$\mathbf{x}(t) = \mathbf{A}(\boldsymbol{\theta})\mathbf{s}(t) + \mathbf{n}(t)\ . \tag{5.1}$$

Here, the columns of the $m \times d$ matrix $\mathbf{A}(\boldsymbol{\theta}) = [\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_d)]$ are the *array propagation vectors*, and $\mathbf{a}(\theta_k)$ models the array response to a narrowband signal with parameter[1] $\boldsymbol{\theta}$. The d-vector $\mathbf{s}(t)$ represents the signal waveforms, and $\mathbf{n}(t)$ is an additive noise term. The array output, $\mathbf{x}(t)$, is measured at N time instants. Based on these observations, one wishes to estimate the number of signals and their parameters. Once these are known, it is a simple task to separate the individual signal waveforms, if desired.

Problems to be addressed in the future work within the area of sensor array processing include the following:

- Most estimation methods require the sensor noise to be independent among the sensors. In many applications this is far from realistic and methods that are applicable in correlated noise fields are beeing developed.
- Parametric techniques require the array response to be known for all possible values of the parameters of interest (calibrated array). Initial steps towards reducing this sensitivity have been taken (see below), but the techniques require further study.
- The asymptotic performance analysis is valid only when the amount of data is much larger than the number of elements in the array. The properties for small amounts of data, but large array size are studied.
- The so-called *subspace-based* methods for array processing have counterparts in state space system identification. Using the techniques developed within this project, these can be analyzed and hopefully related to more traditional identification methods.

5.1 Subspace Fitting Techniques for Signal Parameter Estimation and Detection

A vast number of methods have been proposed in the literature for estimating the directions-of-arrival (DOAs) of the signals. An attempt is made here to examine the relations among many of these techniques, as well as

[1] In general, θ_k can contain several unknown parameters per signal, such as azimuth and elevation angle, polarization, etc. However, some methods are only applicable when θ_k is a real scalar, in this case referred to as the k^{th} *direction-of-arrival* (DOA).

the accuracy of the resulting estimates. In [14], several estimation methods (deterministic ML, MD-MUSIC (Cadzow's method) and TLS ESPRIT) are posed as solutions to different versions of a basic subspace fitting problem. The asymptotic (for large amounts of data) performance of these *subspace fitting methods* is derived and the analysis leads to the introduction of an optimal subspace fitting technique, termed *Weighted Subspace Fitting* (WSF). In [16], a modified Gauss-Newton method for calculating the WSF estimates is proposed. A scheme for estimating the number of sources is also suggested, based on an asymptotic analysis of the WSF criterion function. An extensive comparison with the well-known deterministic ML (least squares) method is performed. The comparison is in terms of: accuracy of the DOA estimate, probability of finding the global minimum of the criterion function, average number of iterations, and capability of detecting the number of sources. The WSF method is found to be preferable in all studied respects.

Total Least Squares (TLS) ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) is a recently proposed estimation method. It is assumed that the array has an *invariance structure*, i.e., it consists of two identical subarrays. Using this assumption, ESPRIT offers an elegant solution to the estimation problem, that requires no numerical search procedure. In [11], the theoretical accuracy of the TLS ESPRIT estimates is derived. The CRB for the "ESPRIT problem" is also introduced, and by numerical examples found to coincide with the estimation error variance for TLS ESPRIT.

Many array structure encountered in practice possess multiple invariances (e.g. uniform linear arrays). It is desirable to exploit the entire invariance structure simultaneously in estimating the signal parameters. In [13] a multiple invariance (MI) ESPRIT algorithm is developed and the asymptotic distribution of the estimates obtained. Simulations and numerical examples are presented to compare the performance of MI ESPRIT with that of several other approaches. The excellent quality of the MI ESPRIT estimates is explained by recent results, see below, which state that, under certain conditions, subspace-fitting methods of this type are asymptotically *efficient*.

5.2 Analysis of Maximum Likelihood and Subspace Fitting Techniques

When the sensor array problem is formulated in an appropriate statistical framework, the Maximum Likelihood (ML) principle provides a systematic way to obtain a parameter estimator. Under certain regularity conditions, the ML estimator is known to be asymptotically *efficient*, i.e., it achieves the Cramér-Rao Bound (CRB) on the estimation error variance. In this sense, ML has the best possible asymptotic properties.

In [12], the relation between the so-called *stochastic* ML (SML) estimator and the weighted subspace fitting technique, described in the previous section, is examined. It is shown that the parameter estimates obtained from the ML method have the same asymptotic distribution as the WSF estimates. Under the Gaussian signal assumption the ML estimator provides efficent estimates and consequently the WSF technique is also efficient. The TLS-ESPRIT and MI-ESPRIT algorithms are subspace fitting techniques and the resulting estimates are also asymptotically efficient *given the information that methods use* (in the ULA case, *all* invariances must be used for the estimates to be efficient). The equivalence of WSF and ML also results in a novel, compact matrix expression for the CRB on the estimation error variance.

In many applications, the signal waveforms are not well-approximated by Gaussian random processes. The asymptotic analysis of the ML and WSF methods is in [12] extended to general emitter signals. The asymptotic properties of the signal parameter estimates are shown to be independent of the actual distribution of the signal waveforms, i.e., the techniques are *asymptotically robust*.

In [15, 5], empirical comparisons of the SML and WSF based techniques for detection and estimation are presented, see also [44]. Also the small sample behaviour appears to be similar for the two. However, the WSF optimization can be implemented using significantly less operations than the stochastic ML technique, [5].

5.3 Adaptive Arrays for Mobile Communication

The rapid increase of the number of users of mobile telephones, places challenging demands on the future communication systems. Frequency hopping and advanced coding techniques have already been implemented to reduce the unavoidable increase of co-channel interference. However, these techniques are inherently limited by the available frequency spectrum.

In order to examine the possibilities of increasing the channel capacity, the concept of sensor array processing is introduced to the area of mobile communication systems, see [9, 30]. The incorporation of directional sensitivity, provided by so-called *adaptive antennas*, offers a new dimension to the reduction of co-channel interference. This directional sensitivity is obtained by employing an antenna array at the base station, possibly both in receiving and transmitting mode. A scheme for separating several signals at the same frequency is proposed. The method is based on high-resolution direction finding followed by an optimum combining. Comparisons to a method based on reference signals are made. Computer simulations are carried out, for testing the applicability of the technique to scattering scenarios that typically arise in urban areas. The proposed scheme is found to have great potential in rejecting co-channel interference, albeit at the expense of high computational requirements.

5.4 Direction Finding in the Presence of Array Uncertainties

It is widely appreciated that the array response models used in sensor array signal processing can give only approximate descriptions of the actual data collection system. Recent studies have shown that "traditional" parametric estimation techniques are quite sensitive to the array response information. Alternative signal parameter estimators that are less sensitive to perturbations in the array manifold have recently been considered within the present project. In [38], a parametrized stochastic model for the array uncertainties is introduced. The unknown array parameters can for example include the individual gain and phase responses of the sensors as well as their positions. Based on this model a maximum *a posteriori* (MAP) estimator is formulated. This results in a fairly complex optimization problem which is computationally expensive. The MAP estimator is simplified by exploiting its relation to the WSF method. An approximate method that further reduces the complexity is also presented, assuming small array perturbations. A compact expression for the MAP Cramér-Rao bound (CRB) on the signal and array parameter estimates is derived and a simulation study indicates that the proposed robust estimation procedures achieve the MAP-CRB even for moderate sample sizes. Theoretical evidence for this last claim will be the subject of future research.

5.5 Dimension Reduction

The interest in performance improvement for DOA estimation algorithms can result in antenna arrays composed of a large number,m, of sensor elements. Since the computational requirements are directly affected by the dimension of the collected data, the burden increases rapidly with the number of sensors. This increase is often proportional to the cube of the dimension of the Element SPace (ESP), m. This is the case, *e.g.*, for high-resolution methods based on eigendecomposition of the array covariance matrix, which requires $\mathcal{O}(m^3)$ operations. Therefore, in order to reduce the computational complexity of the algorithms it is useful to introduce some sort of mapping that reduces the dimension of the data set, from m to r ($r << m$), before performing the signal processing, see [3]. Another advantage is that if the transformation matrix is implemented using analog technology, there is a need for only r analog-to-digital converters, in contrast to the m ones needed for ESP computations. The space into which the set of full dimensional data is mapped is referred to as the Reduced Dimension BeamSpace (RDBS).

One approach to reduce the amount of computations is to employ a linear (matrix) transformation for mapping the full dimension ESP data into the lower dimensional RDBS, and then apply a signal processing algorithm to this new set of data. The main interest is then to analyze under which circumstances it is possible to retain the property of asymptotically achieving the full-dimension CRB, while significantly reducing the dimension of the data set used for the DOA estimation. Somewhat surprisingly, it is possible to obtain very simple analytical expressions for the requirements to be met by an optimal transformation matrix. These expressions rely on knowledge of the functional form of the array (calibrated array of arbitrary geometry) and the true locations of the sources present. This last condition is, however, not limiting the possibilities of using the results derived to outline a design method. If a spatial sector is specified, in which sources of interest are assumed to be located, it is possible for the locations of these sources to be (nearly) optimally estimated in the sense of the full-dimension CRB.

Chapter 6

New Approaches in System Identification, Modelling and Signal Processing

6.1 Numeric-Symbolic Signal Processing

The purpose of this project is to develop tools and methods which make it possible to incorporate symbolic information into the signal processing. With symbolic information we here mean the relations between "named" quantities, e.g., higher/lower concerning peaks in spectra, signals being more/less oscillatory and so forth. Symbolic information is easiest conceived as quantities and rules in a rule-based expert system. A framework for numeric/symbolic signal processing gives several advantages:

- The possibility to include heuristic information.
- The possibility to make the knowledge on which the implemented algorithms are based more explicit. (Declarative programming)
- The possibility to automate tasks where reasoning-based decisions have to be made.

In the project we have developed a software environment, MaMiC, for numeric/symbolic signal processing. The environment consists of three major components

1. MATLAB, The well-known package for numerical calculations.
2. Common-Lisp and Yaps. For implementation of the symbolic processing. Yaps is a rule-based expert system shell.
3. MACSYMA. A package for symbolic mathematics.

The MaMiC environment is described in [30]. The environment is presently applied to various signal processing tasks. Among the applications we can mention the implementation of an intelligent help function to support the use of a system identification software packages. In [40] it is described how the environment can be used for smooth radar trajectories.

In the project we also try to model "non-standard" system, e.g., systems for which one single model is not sufficient. The objective is to develop methods for modelling, filtering and parameter estimation for such systems. Consider the system description

$$y(t) = H(q;\xi)u(t) + e(t) \tag{6.1}$$

where ξ is some unobservable, time-varying parameter, affecting the system behaviour. Different assumptions can be made concerning the variations of ξ. For instance it can be modelled as a Markov process or jump process. The approach in this project is to assume that ξ is an non-observable variable of low dimension, e.g., some linear combination of the system state vector. In the project we try to find methods to automatically find suitable ξ, and identify the system models corresponding to different ξ-values. The proposed method, see [93], is based on a combination of statistical techniques and methods for classification/clustering from pattern recognition. A potentially useful tool for numeric/symbolic signal processing is the use of symbolic reasoning, e.g. in the form of expert systems. An important issue is then how this type of reasoning can be merged with traditional, statistical methods. This question is addressed in [10]. Another application of signal classification and interpretation is reported in [43]. In the paper methods for automatic segmentation of laser range images are presented.

Figure 6.1: A naturally discrete/continuous system

6.2 Modelling Discrete/Continuous Systems

A relatively new research area for the group is to study modelling of more "unconventional" physical systems. By unconventional we mean, in this context, that the model cannot easily be described by differential/difference equations only. There may be a number of "ifs" and "buts" influencing the behaviour of the system.

Such systems either occur naturally, *e.g.* the tank in Figure 6.1, or appear as a consequence of introducing binary actuators, *e.g.* on/off valves, on/off motor controllers etc. A more peripheral reason for dealing with this class of systems, would be searching for qualitative descriptions. Then we might need to partition an otherwise continuous behaviour into a set of qualitative characterstic classes.

Regardless of our intentions – they may be identification, control or diagnosis to mention a few – the main issue is that of modelling the system. We will here give a brief outline of the basic ideas underlying the proposed modelling strategy.

Figure 6.2: The model tree for the tank

6.2.1 Decision Trees

There are at least two potential applications of decision trees to dynamical systems modelling [55, 105]. In either case the internal nodes of the tree carries questions on measured signals (current and delayed versions). These questions are boolean valued for binary trees and gives the direction of traversal when searching for the leaf which contains the "decision" or class label. The simplest kind of question is based on a single signal, such as $u(t-1) < 2.37$, but more complex questions involving several signals, are of course considered as well [63, 67, 34].

The application of decision trees differs only in how the leaves of the tree are labeled. In the first alternative, which will not be elaborated on here any further, the leaves are labeled according to quantized versions of some output signal. One example would be an alarm device predicting if, for example, the water level $x_1(t) \geq h$. In the context of discrete/continuous systems, however, the concept of *Model Trees* is more interesting. Here each leaf of the tree is labeled with a continuous **model**, an *operating mode model*. Here we may use any conventional model structure like *e.g.* differential equations. For the water tank we have the model tree of Figure 6.2 where we have chosen to use bond graphs to represent the operating mode models.

Figure 6.3: The proposed *unifying* bond graph model

6.2.2 Bond Graphs

A bond graph is basically a graphical representation of ordinary state space equations (not necessarily linear). Moreover, the drawing of bond graphs is restricted under a set of strict syntax rules derived from first principles of energy conservation. Thus it is in fact a "high level" *language* for modelling physical systems. The "high level" notion comes from the fact that the syntax rules supports and guides the modelling engineer in his work of deriving a mathematical model when confronting a real physical device.

In the context of discrete/continuous systems, bond graphs may be used as they were originally intended, as description of the operating mode models in the leaves of the tree; Figure 6.2 once again. However, since any non-linearity may be incorporated in bond graphs, it is possible to have a complete system description in terms of **one single** unifying bond graph [107, 106]. The proposed bond graph for the tank is depicted in Figure 6.3. Half arrows are the energy bonds (physical level), full arrows are active bonds carrying signals but zero energy (control level) and lines without arrows are connections carrying logical values (math level).

6.3 Discrete Control

Discrete control or sequential control are common problems in industry. Almost all process plants contain a part which can be described as sequential control, for example when starting or shutting down a process. The formalism we use was developed in artificial intelligence. The world is described by a state and a set of actions which transform the state of the world. An action is thus a function on the state space. The state is described by a number of state variables x_i. Each x_i belongs to a finite set X_i. The actions are described by *pre-*, *post-* and *prevail-conditions*. The pre- and post-conditions describe what is actually changed by the action, while the prevail-condition is a condition which must be true during the performance of the action (that is, both before and after the performance of the action) but is not affected by the action. In this work we have focused on the problem of finding a plan, i.e., a sequence of actions, which transforms a given initial state into a desired final state.

In [112] a class of planning problems called the *SAS-PUS class* is analyzed and a planning algorithm is presented. The restrictions which form the SAS-PUS class can be intuitively described as follows: there are no two actions giving the same result and every action affects only one state variable. Furthermore, if there is one action whose prevail-condition is that, say, a specific valve is open (i.e., the action cannot be executed unless the valve is open) then there must be no action whose prevail-condition is that the same valve is closed. The SAS-PUS class is an extension of the previously analyzed *SAS-PUBS class*, see [62, 22, 21]. The difference between the SAS-PUS class and the SAS-PUBS class is that for problems in the SAS-PUBS class the state variables are binary.

The algorithm presented in [112] uses the knowledge about the actions expressed in the pre-, post- and prevail-conditions to construct a plan, i.e., a set of actions and a partial order which is the execution order. The unordered actions can be performed in parallel. The algorithm is proved to be correct and complete, and it always returns a minimal plan if there is a plan at all. An important fact is that the complexity of the presented algorithm increases polynomially with the number of actions in the given set, while the class of planning algorithms based on exhaustive search increases exponentially with the number of actions.

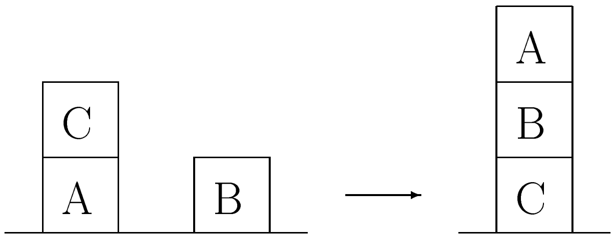

Figure 6.4: Initial and final state for the blocks-world planning problem.

Consider planning in a blocks-world where there are three blocks A, B and C. Initially C is on A, A is on the table and B is on the table. In the final state A should be on B, B on C and C on the table, see Figure 6.3. This problem is known as the Sussman anomaly. Suppose we restict the set of possible actions so that a block which is on top of another block cannot be moved directly to a new block, but has to be moved to the table first. Then the blocks-world planning problem is in the SAS-PUS class, and the algorithm presented in [112] will give a minimal plan.

Chapter 7

Adaptive Control

The activities in the area of adaptive control have been concentrated to an application carried out in cooperation with the Department of Mechanical Engineering. In this application we have studied control strategies for a lorry crane controlled by hydraulic actuators. Modeling this system in detail would be an very difficult task and we have instead chosen to describe the system with a simplified linear model.

The main objective in the design of the control system has been to obtain a closed loop system with well damped responses to changes in the reference or disturbance signal. Using LQG design it has been possible to treat this problem in a systematic way. A presentation of the LQG design is given in [100].

A second objective in the control system design has been to obtain a control system such that the position of the crane tip can be controlled without steady state error also when a constant load disturbance acts on the system. This requirement can be met by a slight modification of the LQG design, such that the control system compensates for the deformation caused by a load applied to the crane. The compensation is based on identification of the mechanical stiffness, which together with measurements of the load pressure give an estimate of the position error. See [20] for further information concerning this approach.

Chapter 8

Differential algebra and nonlinear systems.

When modelling a nonlinear system one might get a large collection of dynamic and static relationships between the physical variables. To get a useful model one has to extract a small number of reasonably simple relationships that give physical insight and/or can be used for numeric simulation. Recently it has become apparent that the framework of differential algebra can be used to make this process systematic.

8.1 Observability

In previous work it has been shown how differential algebra can give insight into the structure of the system. The concept of an autoreduced set can be used to determine the number of necessary input variables. The observability of the system is another property that can be determined. A particularly interesting situation occurs when a certain physical variable is unobservable from a particular output. In this case the output variable satisfies a differential equation of reduced order. In [4] some of these ideas are applied to an estimation problem. The task of estimating the primary current from the secondary in a transformer with possible saturation is considered. This can be regarded as either an observability problem or an inversion problem.

8.2 Nonlinear regulators.

A simple problem formulation for nonlinear regulators is the following. Let the system dynamics be given by

$$F(u, \dot{u}, \ldots, y, \dot{y}, \ddot{y}, \ldots) = 0$$

and let the desired behavior with a reference input r be given by

$$G(r, \dot{r}, \ldots, y, \dot{y}, \ddot{y}, \ldots) = 0$$

Now try to find a feedback law where u is computed from r and y in such a way that the desired performance is achieved.

In [18] it is shown that this is achieved by the controller

$$R(u, \dot{u}, \ldots, y, \dot{y}, \ldots, r, \dot{r}, \ldots) = 0$$

where R is the remainder of G with respect to F in the differential algebraic sense. It is also shown that the zero dynamics of the system, i.e. the dynamics corresponding to identically zero output

$$F(u, \dot{u}, \ldots, 0, 0, 0, \ldots) = 0$$

plays a key role. If the zero dynamics is unstable the procedure is unsuitable.

A simple example of the method is given by

$$F = \dot{y} - y^3 - u, \quad G = \ddot{y} + 2\dot{y} + y - r$$

where the regulator is

$$R = 3y^5 + 2y^3 + 3uy^2 + y + \dot{u} + 2u - r$$

If the system and desired dynamics are

$$F = \ddot{y} - \dot{u} + u^2, \quad G = y^{(3)} + 2\ddot{y} + 2\dot{y} + y - r$$

the regulator is given by

$$R = \ddot{u} + 2(1-u)\dot{u} - 2u^2 - r + y + 2\dot{y}$$

which has the realization (state space description)

$$\dot{x}_1 = x_2 - 2y, \quad \dot{x}_2 = -2(1-x_1)(x_2 - 2y) + 2x_1^2 + r - y, \quad u = x_1$$

However, the zero dynamics is highly unstable:

$$\dot{u} = u^2$$

with a finite escape time.

8.3 Constructive Commutative Algebra in Nonlinear Control Theory

Today the most common mathematical tool in the study of nonlinear systems is probably differential geometry. However, if we consider the subclass of nonlinear systems where all nonlinearities are polynomial it seems more natural to employ methods from commutative algebra. It can be hoped that "nonlinear algebra" (commutative algebra) will be to polynomial systems what linear algebra has been to linear systems. For this to happen we must have access to efficient computational tools, though.

In the past 20 years, algebraists have begun to seriously study a method in elimination theory called Gröbner bases. In some sense Gröbner bases are the analogue of Gaussian elimination for systems of polynomial equations. Algorithms for computing Gröbner bases are available for instance in the symbolic algebra programs Maple and Macsyma.

In [28] some applications of Gröbner bases to nonlinear systems are considered. For example, the problem of determining critical levels of local Lyapunov functions can be tackled with constructive algebra. If V is a local Lyapunov function for a system $\dot{x} = f(x)$ we may consider the system of $n+2$ equations in $n+2$ variables

$$V - d = 0, \quad V_x f = 0, \quad \nabla_x V - \lambda \nabla_x (V_x f) = 0 \tag{8.1}$$

where d is a positive parameter and λ a Lagrange multiplier. Now we can use Gröbner bases to eliminate all variables except d so that we get a polynomial, p say, in d only, which is in the ideal generated by (8.1). The critical value of d now has to be a root of p.

The above ideas can also be used to analyse robustness against structured uncertainty of nonlinear systems. In this case we fix d and let some uncertain parameters η vary, and use elimination theory to determine for which values of η that the region $\{x \mid V(x) < \delta\}$ is stable for a given δ. This approach is studied in [75].

Another example of an application of Gröbner bases is provided by the harmonic balancing method for finding periodic solutions to differential equations. In this method a truncated Fourier series with indeterminate coefficients replaces the unknown function in the original differential equation and thus a system of equations in the coefficients is obtained. If the differential equation in question is polynomial then so is the system of algebraic equations for the coefficients, and elimination theory may be used to analyse the possible periodic solutions.

In nonlinear state space theory Gröbner bases can be of great help. In [104] it is showed how to find the input-output relation for a system in state space form when all nonlinearities are rational functions.

8.4 Nonlinear Systems Analysis Using Computer Algebra Systems

The theory of nonlinear systems has developed rapidly during the last years. However, in order to make use of the comprehensive theory in practice, we need efficient and powerful computational tools as well.

Analysis of nonlinear systems typically requires computations involving symbolic manipulations, e.g. taking derivatives. Therefore, computer algebra systems such as Macsyma, Maple, Mathematica and Reduce have become natural and indispensable tools to use. Using their built-in functions for basic symbolic manipulations we have developed algorithms for solving many problems in nonlinear control theory more or less automatically or at least facilitating the computational work.

Some examples of what we can compute are:

- Basic elements in geometric and algebraic theory like Lie-derivatives, Lie-brackets and characteristic sets.
- Volterra series expansions in input-output descriptions and frequency and step responses using these.
- Coordinate transformations and nonlinear feedback for doing exact linearization.
- Series expansions of Lyapunov functions and solutions to the Hamilton-Jacobi equation.

Having an extensive and powerful toolbox for nonlinear analysis it is possible to use more advanced theory in practical situations, like in the design of controllers for nonlinear systems.

Appendix A

Personnel

Lennart Ljung is professor and head of the control group since 1976. He was born in 1946 and has his Ph.D. in Automatic Control from Lund Institute of Technology. He is currently a Vice President of the International Federation of Automatic Control (IFAC), chairman of the Section for Electrotechnical Sciences in the Royal Swedish Academy of Engineering Sciences, and an associate editor of several journals.

Torkel Glad was born in Lund, Sweden in 1947. He received his M.S. 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 and Optimal Control.

Mille Millnert is a lecturer in the department. He was born in 1952 and received his M.S. in 1977 and his Ph.D. in Automatic Control 1982 from Linköping Institute of Technology. His research interests are Model Based Signal Processing, Parameter Estimation and the Combination of Numerical and Symbolical techniques in Signal Processing and Control.

Bo Wahlberg was born in Norrköping, Sweden, in 1959. He received his M.S. degree in 1983, the Licentiate's degree of Technology in 1985 and the Ph.D. in 1987, all from Linköping Institute of Technology. He is currently a Research Associate in the department. He received the Hugo Schuck Best Paper Award of 1986 American Control Conference. Dr. Wahlberg is an Associate Editor of *Automatica*. His research interests include System Identification, Time Series Analysis and Signal Processing.

Svante Gunnarsson was born in 1959. He is an Associate Professor in the department. He received his M.S. in 1983, Licentiate's degree in 1986 and Ph.D. in 1988 all from Linköping Institute of Technology. His research interests are Identification and Adaptive Control.

Alf Isaksson was born in 1959. He is an Associate Professor in the department. He received his M.S. in 1983 and his Licentiate's degree in 1986 and Ph.D. in 1988, all from Linköping Institute of Technology. His research interests are System Identification and Signal Processing.

Mats Viberg was born in 1961. He is a Research Associate at the department. He received his M.S. in 1985, his Licentiate's degree in 1987 and his Ph.D. in 1989, all from Linköping Institute of Technology. His research interests include Sensor Array Processing, Adaptive Signal Processing and Parameter Estimation.

Björn Ottersten was born in 1961. He received his M.S. degree in electrical engineering and applied physics in 1986 from Linköping University and the Ph.D. degree in electrical engineering in 1989 from Stanford University, USA. During the spring of 1990 he was a Doctoral Fellow at the Information Systems Laboratory, Stanford University. He is currently a Research Associate at the department. His research interests include stochastic signal processing, sensor array processing and parameter estimation.

Peter A J Nagy was born in 1961. He received his M.S. in 1986 and his Licentiate's degree in 1988, all from Linköping Institute of Technology. His research interests are in Artificial Intelligence, especially Expert Systems and their use in control theory and signal processing. He is currently working on a programming environment for combined numeric/symbolic data processing.

Tommy Svensson was born in 1963. He received his M.S. in Applied Physics and Electrical Engineering from Linköping Institute of Technology in 1986. His research interest is nonlinear systems.

Inger Klein was born in 1964. She received her M.S. in 1987 and her Licentiate's degree in 1990, all from Linköping Institute of Technology. Her research interest is Discrete Event Systems and Sequential Control.

Krister Forsman was born in 1963. He received his M.S. in Applied Mathematics in 1987 and his Licentiate's degree in 1990, all from Linköping Institute of Technology. His research interests are applications of differential algebra and algebraic geometry to nonlinear systems.

Ke Wang Chen was born in 1960 and came from Shanghai, China in September 1986. There she specialized in mathematical science in the Mathematics Department of East China Normal University from October 1978 to July 1982. Her research interests are applications of differential algebra to nonlinear systems.

Fredrik Gustafsson was born in 1964. He received his M.S. degree in electrical engineering in 1988 and his licentiate degree in 1990. His current research interests are detection and blind equalization.

Sören Andersson was born in Lund, Sweden, in 1964. He received the M.Sc. and Licentiate of Engineering degrees from Linköping University, Sweden, in 1988 and 1990, respectively. His research interests are in the areas of sensor arrays, digital signal processing and parameter estimation.

Håkan Hjalmarsson was born in 1962. He received his M.S. in 1988 from Linköping Institute of Technology. Presently, his research interest is model quality in system identification.

Jan Erik Strömberg was born in the deep dark forests of Dalarna in 1963. He received his M.S. in Computer Science from Linköping Institute of Technology in 1988. Trees still play an important role in his life, since they are an integral part of his research in non-conventional system identification and modelling.

Roger Germundsson was born in 1965. He received his M.S. in 1989 from Linköping Institute of Technology. His current research interests are in the field of discrete event systems and nonlinear control.

Jonas Sjöberg was born in 1964. He received his M.S. in 1989 from Uppsala University. His current research interest is in the field of nonlinear identification with neural networks.

Torbjörn Andersson was born in 1967. He received his M. S. in 1990 from Linköping Institute of Technology.

Predrag Pucar was born in 1965. He received his M. S. in 1990 from Linköping Institute of Technology.

Peter Lindskog was born in 1965. He received his M. S. in 1990 from Linköping Institute of Technology.

John Hallam was born in 1958 in Jersey, Channel Islands. He graduated from the University of Oxford in 1979 with a first class Honours degree in Mathematics and joined the Department of Artificial Intelligence at the University of Edinburgh as a research student. He was awarded his Ph.D. in 1985. He became a lecturer in the Department of Artificial Intelligence toward the end of 1985 and teaches a masters course in Computational Vision and a course in fundamental knowledge representation techniques to undergraduates. His research interests are Autonomous robotics and Computer Vision.

Sten Granath was born in 1951. He received his M.S. in 1975 from Linköping University, Department of Applied Mathematics.

Patrik Lägermo was born in 1965. He received his M.S. in 1989 from Linköping University, Department of Electrical Engineering. As a research engineer he is responsible for the computer network and the laboratory equipment.

Ingegerd Stenlund and *Ulla Salaneck* are secretaries for the control group. Like everybody else in the department they were born, but at different times. Their interests are earthquakes and tap dancing. That is why they get along so well with the automatic control group.

Appendix B

B.1 Undergraduate Courses

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

Automatic Control Y (Reglerteknik Y). Basic course for the Electrical Engineering and Computer Science Programs. 190 participants. Lecturer: Bo Wahlberg.

Automatic Control M (Reglerteknik M). As above but for the Mechanical Engineering Program. 120 participants. Lecturer:Alf Isaksson.

Automatic Control I (Reglerteknik I). As above, but for the Industrial Economy Program. 160 participants. Lecturer: Svante Gunnarsson, Björn Ottersten.

Automatic Control D (Reglerteknik D). As above, but for the Computer Science Program. 90 participants. Lecturer: Mats Viberg.

Control Theory Y (Reglerteori Y). Advanced course for the Electrical Engineering, Computer Science Program. Sampled data systems, stochastic control, nonlinear systems, system identification. 125 participants. Lecturer: Torkel Glad.

Automatic Control, advanced course (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Sampled data systems, Non-linear systems. 20 participants. Lecturer: Alf Isaksson.

Control Theory I (Reglerteori I). Advanced course for the Industrial Economy Program. Sampled data systems, stochastic control, system identification. 45 participants. Lecturer: Svante Gunnarsson.

Modelling and Simulation (Modellbygge och Simulering). For the Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 95 participants. Lecturer: Torkel Glad.

Modelling of Industrial Systems (Modellering av Industriella System). As above, but for the Computer Science Program. 25 participants. Lecturer: Lennart Ljung.

Digital Control (Digital Styrning). For the Electrical Engineering, Computer Science and Industrial Economy Programs. Numerical control, binary control and PLCS, process computers and applications of digital process control. 180 participants. Lecturer: Mille Millnert.

Digital Signal Processing (Digital Signalbehandling) For the Electrical Engineering Program. Spectral estimation, Wiener and Kalman filtering, Adaptive Signal Processing. 70 participants. Lecturer: Mille Millnert.

Control Project Laboratory (Reglerteknisk Projektkurs). For the Electrical Engineering and Computer Science Programs: Modelling and identification of a laboratory process. Controller design and implementation. 26 participants. Lecturer: Svante Gunnarsson.

B.2 Graduate Courses

Differential algebra and nonlinear control. Lecturer: M. Fliess. Literature: Lecture Notes.

Linear Systems. Lecturer: B. Wahlberg. Literature: T. Kailath: *Linear Systems*, Prentice-Hall, Inc. Englewood Cliffs, N.J. 1980.

Robust Control. Lecturer: L. Ljung. Literature: J.M. Maciejowski *Multivariable Feedback Design*, Addison-Wesley Publishing Company, 1989.

Appendix C

Computers and Laboratory Equipment

- A computer network with a Sun SPARC system 300 server and 1 Sun 386i, 1 Sun SPARCstation1+, 5 SPARCstation 2 and 19 SPARCstation SLC.
- 11 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
- 1 air-driven generator plant
- 1 air-driven steam generator
- 1 hot water heating process
- 1 coupled tanks process (level control by Tecquipment)
- 1 “ball and beam” process by Tecquipment

- 1 “ball and hoop” process by Tecquipment
- 3 Lego processes for sequential control
- 8 Ericsson AT computers with Metrabyte Dash 16 interfaces (A/D, D/A and digital I/O).
- 1 Ericsson AT computer with AT&T DSP32C signal processor.
- 1 Compaq Deskpro 386 computer with the SattLine software.

Appendix D

Seminars

Optimal eigenanalysis methods for frequency estimation. Dr Petre Stoica, Inst Politecnic Bucuresti, Bukarest, Rumania. August 2, 1990.

Adaptive control using a projection algorithm. Dr Iven Mareels, University of Newcastle, Australia. August 6, 1990.

Nonlinear control using Penfold's ideas on local control. Dr Iven Mareels, University of Newcastle, Australia. August 7, 1990.

Playing with toy cars. Dr John Hallam, Edinburgh University, UK. September 11, 1990.

On gray box identification. Dr Stefan Graebe, Automatic Control, Royal Institute of Technology, Stockholm Sweden. September 21, 1990.

Tracking using state estimates for robot applications. Professor C. Canudas de Wit, Laboratoire d'Automatique de Grenoble, France. October 16, 1990.

Tuning the technical university education towards Western standards. Professor Boris Tamm, Head of the Tallinn Institute of Technology, Estonia. October 18, 1990.

Sonar engineering research at Loughborough University of Technology. Professor J. W. R. Griffiths, Dept of EEE, Loughborough University of Technology, UK. October 19, 1990.

On some issues in system identification. Professor Graham Goodwin, University of Newcastle, Australia. November 8, 1990.

On some other issues in system identification. Professor Michel Gevers, Universite Catholique de Louvain, Belgium. November 8, 1990.

Conditions for informative data sets in system identification. Professor Yuan Zhen-Dong, Dept of Mathematics, East China Normal University, Shanghai, China. November 22, 1990.

The prequential approach to statistics. Professor Philip Dawid, Dept of Statistical Sciences, Univ. College, London, UK. November 26, 1990.

A procedure and power distribution inequalities - A new approach in optimization and robustness of uncertain systems. Professor Alex Megrevitsky, Leningrad. December 6, 1990.

A speed gradient method for adaptiv control. Professor Alexander Fradkov, Leningrad. February 5, 1991.

Applications of Kalman filter in meteorology. Meteorologist Anders Persson, SMHI, Norrköping, Sweden. February 14, 1991.

Modelling of packed bed distillation columns. Dr Anders Karlström, Holmen Paper AB, Sweden. April 25, 1991.

Robust classification of known signals. Dr Ola Hössjer, Dept of mathematics, Uppsala University, Uppsala, Sweden. May 2, 1991.

Optimal control of piecewise/deterministic Markov processes. Professor Mark Davis, Imperial College, London, UK. May 6, 1991.

Chaos in Kalman filtering. Professor Anders Lindquist, Royal Institute of Technology, Stockholm, Sweden. May 24, 1991.

Qualitative reasoning and bond graphs. Dr Jan Top, Netherland Energy Research Foundation ECN. May 27, 1991.

Some important aspects of human movement analysis. Dr Virgil P. Stokes, Physiology III, Karolinska Institutet, Stockholm, Sweden. June 6, 1991.

Appendix E

Lectures by the staff

I. Klein: *Planning in Polynomial Time: The SAS-PUBS Class* International Workshop on Expert Systems in Engineering, Vienna, Austria, October 24-26, 1990.

S. Andersson: *A Study of Adaptive Arrays for Mobile Communication Systems.* 1991 annual International Conference on Acoustics, Speech and Signal Processing in Toronto, Canada, May 14-17 1991.

S. Andersson: *Tillämpningar av array processing inom digital kommunikation.* STU, Digital Communication. Gothenburg, Sweden, May 29 - 30, 1991.

J. Sjöberg: *Issues on Black-Box Identification with Neural Networks.* ETH-Zentrum, Zürich, Switzerland, March 6, 1991.

L. Ljung: *Model accuracy in system identification.* IFAC Symposium on Intelligent Tuning and Adaptive Control, Singapore, January 1991.

L. Ljung: *A Tutorial on System Identification.* IFAC Symposium on Intelligent Tuning and Adaptive Control, Singapore, January 1991.

L. Ljung: *Model structure identifiability and persistence of excitation.* 29th Conference on Decision and Control, Hawaii, USA, December 1990.

L. Ljung: *On the accuracy of identified models*. May 23, 1991, Luleå Institute of Technology, Sweden.

L. Ljung:*Estimating model accuracy*. IIASA Sumposium on Modelling and Control of Uncertain Systems, Sopron, Hungary, September 3, 1990.

L. Ljung: *On the accuracy of identified models*. 5th Leningrad Symposium on the Theory of Adaptive Systems, (TAS '91), Leningrad, April 17, 1991.

L. Ljung: *On the identifiability of systems*. Technical University of Vienna, Vienna, Austria, April 26, 1991.

L. Ljung:*Differential algebra and parameter identifiability*. ETH-Zentrum, Zurich, Switzerland, May 13, 1991.

L. Ljung: *Using advanced sofware facilities for model structure selection*. ETH-Zentrum, Zurich, Switzerland, May 14, 1991.

L. Ljung: *Identifying state-space models using Mathwork's system identification toolbox*. ETH-Zentrum, Zürich, Switzerland, May 15, 1991.

L. Ljung: *Model accuracy in system identification*. ETH-Zentrum, Zürich, Switzerland, May 15, 1991.

S.Gunnarsson: *Adaptive compensation of deformations in mechanical structures controlled by hydraulic actuators*. 11th IFAC World Congress, Tallin, Estonia, August 16, 1990.

F. Gustafsson: *Optimal segmentation*. Lund University, November 19 1990.

F. Gustafsson: *Optimal segmentation in a linear regression framework*. 1991 annual International Conference on Acoustics, Speech and Signal Processing in Toronto, Canada, May 14-17 1991.

H. Hjalmarsson: *Estimation of the variability of time-varying systems*. Baltic Olympiade on Automatics, Leningrad, June 25-27, 1991.

J.E. Strömberg: *Modellstrukturer för dynamiska system med diskreta inslag* (Model structures for dynamical systems with discrete elements). DUP meeting, STU, Stockholm, March 12, 1991.

J.E. Strömberg, A. Isaksson: *Neural Trees - Using Neural Nets in a Tree Classifier Structure*. The International Conference on Acoustics, Speech and Signal Processing (ICASSP '91), Toronto, Canada, May 14, 1991.

P. Nagy: *Numeric / Symbolic Signal Processing : Tools and Applications*. Scandinavian CACE Symposium. Lyngby, Denmark, Nov 15 - 16, 1990.

P. Nagy: *Numeric / Symbolic Signal Processing*. STU, Digital communication. Gothenburg, Sweden, May 29 - 30, 1991.

T. Svensson: *Nonlinear Systems Analysis Using Formula Manipulating Languages*. Nordic CACE Symposium, Lyngby, Denmark, Nov 15-16, 1990.

K. Forsman: *Controller Design and Analysis Using Computer Algebra* Scandinavian CACE Symposium. Lyngby, Denmark, November 15-16, 1990.

K. Forsman: *Applications of Gröbner Bases in Control Theory* Lund Institute of Technology, Dept. of Aut. Control, Lund, Sweden, November 2, 1990.

K. Forsman: *Applications of Constructive Algebra to Control Problems* Courant Institute of Mathematical Science. New York, USA, December 3, 1990.

K. Forsman: *Constructive Algebraic Geometry in Nonlinear Control* 29th Conf. Decision and Control. Honolulu, USA, December 7, 1990.

K. Forsman: *Applications of Differential and Commutative Algebra to Nonlinear Control Theory* Stockholm University, Mathematical Dept. Stockholm, Sweden, April 7, 1991.

A. Isaksson: *Modelling of industrial processes* (In Swedish). CMD, Uppsala University, November 12-13, 1990.

A. Isaksson: *System Identification subject to missing data* (In Swedish). Department of Mathematical Statistics, Lund Institute of Technology, December 10, 1990.

A. Isaksson: *System identification – an introduction* (In Swedish). College of Karlstad, May 2, 1991.

A. Isaksson: *Estimation of retention times using system identification* (In Swedish), Conference at STFI, Stockholm, June 6, 1991.

A. Isaksson: *Neural Trees - Using Neural Nets in a Tree Classifier Structure.* Department of Electrical Eng., Yale University, New Haven, USA, June 20, 1991.

A. Isaksson: *System identification subject to missing data.* American Control Conference (ACC-91), Boston, USA, June 26, 1991.

T. Glad: *Nonlinear regulators and Ritt's remainder algorithm.* Colloque International sur l'Analyse des Systèmes Dynamiques Controlés, Lyon, France, July 5, 1990.

T. Glad: *Parametrization of nonlinear model structures as linear regressions.* 11th IFAC World Congress, Tallinn, Estonia, August 13, 1991.

T. Glad: *A changed point of view for optimization in control theory.* ITM conference, Göteborg, June 13, 1991.

B. Ottersten: *Asymptotic Analysis of SVD-Based Array Processing Algorithms.* SIAM Conference on Linear Algebra, San Francisco, CA, November 5-8, 1990.

B. Ottersten: *Robust Signal Parameter Estimation in the Presence of Array Perturbations.* 1991 annual International Conference on Acoustics, Speech and Signal Processing in Toronto, Canada, May 14-17 1991.

M. Viberg: *Array Processing.* STU, Digital Communication. Gothenburg, Sweden, May 29 - 30, 1991.

B. Wahlberg: *Robust Frequency Domain Fault Detection/Diagnosis,* 11th IFAC World Congress, Tallinn, Estonia, August 13, 1991.

B. Wahlberg: *Factorizations that Relax the Positive Real Condition in Continuous-time ELS Schemes*, 11th IFAC World Congress, Tallinn, Estonia, August 13, 1991.

B. Wahlberg: *Approximate Modelling by means of Orthonormal Functions.* IIASA Symp. on Modeling and Control of Uncertain Systems, Sopron, Hungary, September 3, 1990.

B. Wahlberg: *On estimation of transfer function error bounds*, Caltech, USA, December 3, 1990.

B. Wahlberg: *Some Asymptotic Results in Recursive Identification using Laguerre Models.* 29th Conf. Decision and Control. Honolulu, USA, December 5, 1990.

B. Wahlberg: *On estimation of transfer function error bounds*, Department of Mechanical Engineering and Marine Technology, Delft University of Technology, Delft, The Netherlands, May 3, 1991.

B. Wahlberg: *Approximate Modelling by means of Orthonormal Functions*, Department of Mechanical Engineering and Marine Technology, Delft University of Technology, Delft, The Netherlands, May 14, 1991.

B. Wahlberg: *On estimation of transfer function error bounds*, University of Groningen, Groningen, The Netherlands, May 27, 1991.

B. Wahlberg: *On estimation of transfer function error bounds*, CWI, Amsterdam, The Netherlands, May 28, 1991.

B. Wahlberg: *Some issues in system identification*, Department of Mechanical Engineering and Marine Technology, Delft University of Technology, Delft, The Netherlands, May 31, 1991.

B. Wahlberg: *On estimation of transfer function error bounds*, Phillips Research Lab, Eindhoven, The Netherlands, June 3, 1991.

B. Wahlberg: *Identification and Approximation of Linear Systems Using Laguerre/Kautz Models*, Systems Theory Day, University of Twente, Enschede, The Netherlands, June 18, 1991.

B. Wahlberg: *Black-Box Modelling using a Priori Information*, IIASA Workshop: From Data to Model, Laxenburg, Austria, June 24, 1991.

M. Millnert:*Numeric symbolic signal processing with application to radar tra-*

jectory smoothing. 5th European Signal Processing Conference, Barcelona, Spain, September 18-21, 1990.

Appendix F

Travel and Conferences

Lennart Ljung took part in the 11th IFAC World Congress in August 1990 in Tallinn, and in September 3-7 he attended the IIASA meeting on Modelling and Control of Uncertain Systems in Sopron, Hungary. In December 5s-7 he participated in the CDC meeting in Honolulu and in January 14-18 he attended the IFAC Symposium on Intelligent Tuning and Adaptive Control in Singapore. On March 11 he was external examiner for a Ph.D. thesis in Trondheim, Norway. April 16-19 he attended the 5th Leningrad Symposium on the Theory of Adaptive Systems and April 24-28 he participated in the IFAC Presidents' meeting in Laxenburg, Austria. He was an invited lecturer at the ETH-Zentrum in Zürich, May 13-17, and visited the Luleå Institute of Technology on May23, 1991.

Torkel Glad took part in "Colloque International sur l'Analyse des Systèmes Dynamiques Controlés" in Lyon, France, July 3-6 1990, in the 11th IFAC World Congress in Tallinn in August 13-17, 1990 and in the Conference ITM-91 in Gothenburg, June 12-13 1991.

Mille Millnert participated in the 3rd European Signal Processing Conference in Barcelona, Spain. In October he also attended the "Reglermöte '90" in Linköping, Sweden. In December he participated in the 29th CDC Conference in Honolulu, Hawaii and in May he attended the STU Workshop on Digital Communication, Gothenburg, Sweden.

Svante Gunnarsson visited the "11th IFAC World Congress", August 13-17, Tallin Estonia.

Alf Isaksson visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia, USSR. He visited CMD, Uppsala University, November 12-13, 1990. On December 10-11, 1990, he visited Department of Mathematical Statistics, Lund Institute of Technology. He also participated in a one-day conference, March 12, 1991, in Stockholm, organized by STU (the Swedish Technical Board for Technical Development). On various occasions during the year he has visited the College of Karlstad and the STORA paper mill in Skoghall, and also the Swedish Pulp and Paper Research Institute (STFI) in Stockholm. He also visited STORA Cell AB in Skutskär, May 6, 1991. On May 14 - 17, 1991, he participated in the annual International Conference on Aucustics, Speech and Signal Processing (ICASSP '91) held in Toronto, Canada. He visited Department of Electrical Eng. at Yale University, New Haven, USA, June 19-21, 24, 1991, and after that attended the American Control Conference (ACC-91) in Boston June 26-28. On the same trip he also visted Pulp and Paper Reserch Institute Canada (PAPRICAN), in Montreal, July 2, 1991.

Bo Wahlberg visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia, USSR. In September 3 –7 he attended the IIASA meeting On Modeling and Control of Uncertain Systems in Sopron, Hungary. On December 3, 1990, he visited Caltech, USA, and December 5-7 he participated in the 29th CDC in Honolulu, Hawaii. B. Wahlberg spent the period April 22- June 22, 1991 at Department of Mechanical Engineering and Marine Technology, Delft University of Technology, Delft, The Netherlands. This visit was financed by the Dutch Network on Systems and Control. During this visit he also visited University of Groningen, CWI (Amsterdam), Phillips Research Lab (Eindhoven), University of Twente (Enschede). In June 24 – 28 he attended the IIASA workshop From Data to Models, in Laxenburg, Austria.

Mats Viberg attended "Reglermöte '90" October 24-25, Linköping, Sweden. He participated in the "1991 Annual International Conference on Acoustics, Speech and Signal Processing", 14-17 May 1991 in Toronto, Canada. He also attended the "STU - Digital Kommunikation"-meeting, May 29-30, 1991, Gothenburg, Sweden.

Björn Ottersten attended the "24$^{\text{th}}$ Asilomar Conference on Signals Systems and Computers, Nov., 1990, in Monterey, California, as well as the SIAM Conference on Linear Algebra, Nov., 1990, in San Francisco, California. He visited the Department of Electrical Engineering at Stanford University, California during Nov., 1990, and also visited Lockheed Research Lab. in Palo Alto, California. In October 24-25 he attended "Reglermöte '90" in Linköping, Sweden. He participated in the "1991 Annual International Conference on Acoustics, Speech and Signal Processing" 14-17 May 1991 in Toronto, Canada. He also participated in the "STU - Digital Kommunikation"-meeting, May 29-30, 1991, Gothenburg, Sweden.

Jan-Erik Strömberg participated in a one-day conference, March 12, 1991, in Stockholm, organized by STU (the Swedish Technical Board for Technical Development). On May 14 - 17, 1991, he participated in the annual International Conference on Aucustics, Speech and Signal Processing (ICASSP '91) held in Toronto, Canada. On June 24, 1991, he visited an Esprit information seminar organized by STU and held in Stockholm.

Inger Klein visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia. She participated in the workshop "Expert Systems in Engineering", September 24-26, Vienna, Austria and the Fifth International Symposium on Methodologies for Intelligent Systems, October 25-27, Knoxville, USA, 1990.

Krister Forsman visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia. On October 24-25 he participated in "Reglermöte '90" in Linköping, Sweden. On November 2, 1990, he visited Lund Institute of Technology, Lund Sweden.He also participated in the "Nordic CACE Symposium", November 15-16, 1990, Lyngby, Denmark. On December 3, 1991, he visited the Courant Institute in New York, and December 5-7 he participated in the 29th CDC in Honolulu, Hawaii. On various occasions during the year he has visited the Royal Institute of Technology in Stockholm and the Department of Mathematics at Stockholm University. He visited Chalmers Institute of Technology, Gothenburg, on May 27, 1991.

Tommy Svensson visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia. In October 24-25 he participated in "Reglermöte '90" in Linköping, Sweden. He also participated in the "Nordic CACE Symposium", November 15-16, 1990, Lyngby, Denmark.

Sören Andersson visited the "11th IFAC World Congress", August 13-17, 1990, in Tallinn, Estonia. In October 24-25 he attended “Reglermöte ’90” in Linköping, Sweden. He participated in the “1991 Annual International Conference on Acoustics, Speech and Signal Processing” 14-17 May 1991 in Toronto, Canada. He also participated in the “STU - Digital Kommunikation”-meeting, May 29-30, 1991, Gotenburg, Sweden.

Håkan Hjalmarsson visited the “11th IFAC World Congress”, August 13-17, 1990, in Tallinn, Estonia. During March 21-22, 1991 he visited the conference “Robust Control System Design using H^∞ and Related Methods” at the University of Cambridge, UK. He also visited the Leningrad Branch of the USSR Information and Computer Society during June 24-28 where he participitated in the “Baltic Olimpiade on Automation”, June 25-27.

Fredrik Gustafsson visited the “11th IFAC World Congress”, August 13-17, 1990, in Tallinn, Estonia. He participated in the “1991 annual International Conferenence on Acoustics, Speech and Signal Processing” 14-17 May 1991 in Toronto, Canada. He gave a seminar at Lund University 19 November 1990.

Jonas Sjöberg visited “11th IFAC World Congress”, August 13-17, 1990, in Tallinn, Estonia. March 4-8, 1991 he visited ETH, Zürich, Switzerland.

Torbjörn Andersson visited STORA Cell AB in Skutskär, May 6, 1991. On various occasions during the year he has visited the Swedish Pulp and Paper Research Institute (STFI) in Stockholm.

Predrag Pucar visited STORA Cell AB in Skutskär, May 6, 1991. On various occasions during the year he has visited the Swedish Pulp and Paper Research Institute (STFI) in Stockholm.

Peter Nagy Participated at “Scandinavian CACE symposium”, November 15-16, 1990, in Lyngby, Denmark. He also took part in “STU - Digital Kommunication”, May 29-30, 1991, Gotenburg, Sweden.

Ulla Salaneck and Ingegerd Stenlund visited the IFAC Secretariat in Laxenburg, Austria in May 1991.

The whole group took part in the Reglermöte 90, October 1991 in Linköping, Sweden.

Appendix G

Publications

Licentiate Theses

[1] F. Gustafsson, “Optimal segmentation of linear regression parameters”, Technical Report Thesis No 246, ISSN 0280-7971, ISBN-91-7870LiTH-ISY-I-1160, Linköping University, Linköping Sweden, September 1990.

Abstract

The problem of detecting multiple changes in the dynamical properties of a measured signal, which we call *segmentation*, is studied. A Bayesian model-based approach is used. The signal is supposed to be described by a linear regression. The posterior distribution for the change instants is first derived for a quite general signal model. Three special choices of signal model are then proposed for segmentation. The maximum *a posteriori* (MAP) estimate is studied. It is shown that it contains the estimates from the maximum likelihood method and the generalized likelihood ratio test as special cases.

This posterior distribution contains a number of components which increases exponentially in the number of measurements, t. Nevertheless, it is shown that under certain assumptions on the parameter variation structure, the number of components that really have to be examined increases considerably less than t. this exact pruning possibility is shown to be asymptotically efficient in the ratio between the jump magnitude and the noise variance.

For the general signal model a recursive search scheme is proposed to approximate the MAP estimate. Segmentation examples and other possible applications of the search scheme are given.

[2] H. Hjalmarsson, "On estimation of model quality in system identification", Technical Report Thesis no. 251, ISSN 0280-7971, ISBN 91-7870-723-4, Linköping University, Linköping, Sweden, November 1990.

Abstract

The rapidly expanding area of robust control has created new demands on the characterization of the deviation between a model and the true system. As a consequence, the issue of model quality has come to be central in system identification.

The *model error* is sthe total error between the true system and the model. This can be divided into two terms, *random error* and *bias error* corresponding to the error due to measurement noise and model structure mismatch, respectively.

Estimation of the random error requires in principle no knowledge about the true system while prior information is crucial when assessing the under-modeled dynamics. A survey of this subject is given. The true expression for the random error is known but complex and not easily estimated. A simple and explicit estimation method that is consistent even in the case of severe under-modeling is given.

We also consider time-varying systems that vary around an "average" system. For such systems without feedback it is impossible to distinguish the time-variantions from an incorrect noise model with respect to the second order properties of the signals. We present a simple elast squares method to detect and estimate a bound on the variations in the frequency domain.

[3] S. Andersson, "Sensor Array Processing; Application to Mobile Communication Systems and Dimension Reduction", Technical Report Thesis no. 255, ISSN 0280-7971, ISBN 91-7870-730-7, Linköping University, Linköping, Sweden, November 1990.

Abstract

In recent years it has become evident that various problems from nonlinear system theory can be solved by using differential algebraic techniques. The purpose of this thesis is to apply this mathematical framework on observability and invertibility of nonlinear systems. These properties are of fundamental importance in determining some physical variables from some other variables of any practical system. Sufficient and necessary conditions for testing observability and invertibility of a nonlinear system via its characteristic sets are presented in the thesis.

We also propose some design methods for a practical nonlinear system - a current transformer with saturation.

[4] Ke Wang Chen, Observability and invertibility of nonlinear systems: A differential algebraic approach, Technical Report Thesis no. 282, ISSN 0280-7971, ISBN 91-7870-791-9, Linköping University, Linköping, Sweden, April 1991.

Abstract

In recent years it has become evident that various problems from nonlinear system theory can be solved by using differential algebraic techniques. The purpose of this thesis is to apply this mathematical framework on observability and invertibility of nonlinear systems. These properties are of fundamental importance in determining some physical variables from some other variables of any practical system. Sufficient and necessary conditions for testing observability and invertibility of a nonlinear system via its characteristic sets are presented in the thesis. We also propose some design methods for a practical nonlinear system - a current transformer with saturation.

Journal Papers

[5] B. Ottersten, M. Viberg, P. Stoica, and A. Nehorai, Exact and large sample SML techniques for parameter estimation and detection in array processing, Technical report, LiTH-ISY-I-1164, 1991.

[6] V. Krishnamurthy, B. Wahlberg, and J. Moore, "Factorizations that Relax the Positive Real Condition in Continuous-time and Fast-Sampled ELS Schemes", *Int. J. Adapt. Control Signal Process*, **4**(5):389–414, Sep. 1990.

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Appendix H

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Appendix I

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