Eleventh conference on the mathematics of Operations research and system theory including the Benelux meeting on systems and control 1986

JANUARY 15-17, 1986

CONFERENCE CENTER "DE BLIJE WERELT"

LUNTEREN, THE NETHERLANDS

Organized by the
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AIM AND SCOPE

The aim of the conference is to promote the research activities and the cooperation between researchers in the mathematics of operations research and system theory.

The program of the conference consists of a plenary part, and parallel sessions of operations research and systems and control. The plenary part of the program contains

- a lecture on operations research by P. Whittle,
- a lecture on systems and control by J.P. Quadrat,
- a three-hour minicourse on networks of queues organized by J. Wessels.

In addition there will be,

- seven lectures on operations research,

in parallel with

- three lectures on systems and control,
- and 29 short presentations on this subject by Benelux researchers.

The program should give ample opportunity for informal discussions.

ORGANIZATION

Organizers

The conference is organized by the Centre for Mathematics and Computer Science in Amsterdam, in particular by B.J. Lageweg, J.M. Schumacher, A.K. van den Berg and J.H. van Schuppen.

Sponsors
The conference is organized under the auspices of the Dutch Research Community in the Mathematics of Operations Research and System Theory, the Dutch Research Community in the Engineering of System and Control Theory, the NFWO-FNRS contactgroup Automatica-Automatique and the BIRA-Werkgroep System Theory.

Organization Committee Benelux Meeting:
J. van Amerongen (Delft), R.K. Boel (Gent), F.M. Callier (Namur), J.W. Nieuwenhuis (Groningen), G.J. Olsder (Delft), T. Schilperoort (Marknesse), and J.M. Schumacher (Amsterdam).

PROGRAM

Invited speakers
A.R. Conn (Waterloo/Grenoble): Nonlinear programming, exact penalty functions and projection techniques for non-smooth functions; On numerical methods for continuous location problems, including the handling of degeneracy.

G. Cornuéjols (Carnegie-Mellon/Grenoble): New developments in facility location theory; Two algorithms for weighted matroid intersection.

R.P. Guidorzi (Bologna): System identification using canonical forms and overlapping models; Application of identification techniques to the management of natural resources.

T.J. Ott (Holmdel): State dependent routing of telephone traffic and the use of separable routing schemes; Numerical methods for the single server queue.

J.P. Quadrat (Paris): A theoretic system approach of timed discrete event systems; Identification and control of diffusion processes: an expert system.

P. Whittle (Cambridge, UK): Tractable modes of interaction in multi-component systems; Queueing networks, communication networks and optimal routing.

Minicourse: Networks of queues
The minicourse will be used to give an overview of techniques to analyse networks of queues. Particular attention will be given to numerical analysis of large complex systems and to control in networks of queues. The course is organized by J. Wessels (Eindhoven).

The speakers and the titles of the lectures are:
1. A. Hordijk (Leiden): Reversibility and product-form solution in queueing networks;
2. J. Wessels and J. van Doremalen (Eindhoven): Numerical analysis of queueing networks;
3. R.K. Boel (Gent): Control aspects of networks of queues.

Contributed short lectures in systems and control
T. Backx, A. Damen, P. Janssen, P. van den Hof, A. van den Boom (Eindhoven): Equation error and output error methods in multivariable process identification; modelling of a glass tube production process

P. Boekhoudt (Enschede): Comparison of H^∞-optimal feedback control system design methods

J. Bontsema (Groningen): Comparison of some PDE models for flexible structures

F.M. Callier (Namur): On the factorization of row-column-reduced polynomial matrices

B. de Moor, J. Vandewalle (Leuven): The use of non-conventional matrix calculus in linear system theory

J. Engwerda (Eindhoven): On the set of obtainable reference trajectories using minimum variance control

C. Heij (Groningen): Linear finite time systems

J. Katupitiya, H. van Brussel (Leuven): Time-optimal control of a robot using time-varying switching lines

M. Kinnaert (Brussels): Modified discrete time computed torque methods for high precision robot control

D.F. Kuiper (Delft): Effects of structural flexibility on space-manipulator control system design

E.J. Meerwaldt, J. de Goede, A. Berkenbosch (Delft/Leiden): On the parameter estimation of the respiratory control system

C. Merckx (Namur): Identification of a spatially varying parameter in a time-periodic parabolic system

H.E. Nusse (Groningen): Complicated dynamics in simple processes

G.J. Olsder (Delft): On minimal realizations of discrete-event dynamic systems

P.O. Passenier, H.R. van Nauta Lemke (Delft): Design of an optimal vision-based classification system for robots

J.W. Polderman (Amsterdam): On two subsets of the parameter space in adaptive control problems

S.A. Smulders (Amsterdam): Avoiding the development of congestion on a freeway: modeling and prediction of traffic flow

F.B. Sperling (Delft): Piecewise linear robot servo control, a feasible approach

D. ten Hove (Enschede): Collision avoidance of aircraft: an application of stochastic control theory
Families of linear quadratic problems: continuity properties

A.J. Udink ten Cate (Wageningen): Continuous-time constrained least-squares algorithms for recursive parameter estimation of stochastic linear systems by a stabilized output error method

P. van den Hof, T. Backx, A. Damen, P. Janssen, A. van den Boom (Eindhoven): Equation error and output error methods in multivariable process identification; models and criteria

A.J. van der Schaft (Enschede): Nonlinear control theory and robot manipulator control

J.W. van der Woude (Eindhoven): Disturbance decoupling and output stabilization by measurement feedback

J.H. van Schuppen (Amsterdam): Stochastic realization and factor analysis

J. van Vugt, M.J.L. Tiernego (Enschede): Control of an elastic servo system

P.Th.L.M. van Woerkom (Amsterdam): Mathematical model order reduction for the control of flexible spacecraft: a discussion of approaches

J. Winkin, F.M. Callier (Namur): The graph metric for SISO linear distributed systems

H.J. Zwart (Groningen): Invariance concepts for infinite-dimensional systems

SUMMARIES

The summaries are listed below.

TIME SCHEDULE

Time	Plenair	OR	SC1	SC2
Wednesday January 15, 1986				
11:25	Opening			
11:30	Whittle (1)			
12:30	Lunch break			
14:00			Van Woerkom	Meerwaldt
14:30			Bontsema	Udink ten Cate
15:00			Kuiper	Merckx
15:30	Tea break			
16:00		Cornuéjols (1)	Guidorzi (1)	
17:00		Conn (1)	Boekhoudt	Van den Hof
17:30		„	Polderman	Backx
18:00	End			
Thursday January 16, 1985				
09:00	J.P. Quadrat (1)			
10:00	Coffee break			
10:30	Minicourse (1)			
11:30		Conn (2)	Guidorzi (2)	
12:30	Lunch break			
14:00	Minicourse (2)			
15:00	Tea break			
15:30		Ott (1)	Olsder	Van der Woude
16:00		„	Nusse	Zwart
16:30		Whittle (2)	Heij	Winkin
17:00		„	Van Schuppen	
17:45	Vergadering			
Friday January 17, 1985				
09:00	Minicourse (3)			
10:00	Coffee break			
10:30		Cornuéjols (2)	Van der Schaft	Callier
11:00		„	Katupitiya	De Moor
11:30		Ott (2)	Van Vugt	Engwerda
12:00		„	Passenier	Trentelman
12:30	Lunch break			
13:30			Sperling	Ten Hove
14:00			Kinnaert	Smulders
14:30			Quadrat (2)	
15:30	Tea			

CONTRIBUTED SHORT LECTURES IN SYSTEMS AND CONTROL - OVERVIEW OF SESSIONS

Time	SC1	SC2
Wednesday January 15, 1986		
	Flexible structures in space	*Identification 1*
14:00	Van Woerkom	Meerwaldt
14:30	Bontsema	Udink ten Cate
15:00	Kuiper	Merckx
	Robust and adaptive control	*Identification 2*
17:00	Boekhoudt	Van den Hof
17:30	Polderman	Backx
Thursday January 16, 1986		
	Realization and modelling	*Linear systems 1*
15:30	Olsder	Van der Woude
16:00	Nusse	Zwart
16:30	Heij	Winkin
17:00	Van Schuppen	
Friday January 17, 1986		
	Robotics 1	*Linear systems 2*
10:30	Van der Schaft	Callier
11:00	Katupitiya	De Moor
11:30	Van Vugt	Engwerda
12:00	Passenier	Trentelman
	Robotics 2	*Stochastic control*
13:30	Sperling	Ten Hove
14:00	Kinnaert	Smulders

EQUATION ERROR AND OUTPUT ERROR METHODS IN MULTIVARIABLE PROCESS IDENTIFICATION; MODELLING OF A GLASS TUBE PRODUCTION PROCESS

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SUMMARY

In this paper the results are presented obtained by applying the identification algorithms discussed in the companion paper [1] to data measured at the shaping part of a glass tube production process.
Important parameters of a glass tube are its dimensions wall-thickness and diameter. The dimensions of the tube are mainly determined by two process inputs, the pressure and the drawing speed. The developed algorithms are applied for the modelling of the shaping part of the glass tube production process.
The constructed model has two inputs (pressure and drawing seed) and two outputs (wall-thickness and diameter).
In this paper a short description is given of the process. A comparison is made between the results obtained from the various identification algorithms as presented in [1]. The corresponding models are classified by the chosen model set, its parametrization, the identification criterion and the identification method.
The quality of the model is judged on the ability of the model to simulate the dynamical behaviour of the process. The impulse responses, the eigen values and the fit to the data used for the estimation are given.
The various models are used to simulate the process behaviour on a data set different from the one used for the estimation of the model parameters. The simulation results are compared with the actual measured process behaviour.

[1] Paul Van den Hof et.al: Equation error and output error methods in multivariable process identification; models and criteria. To be presented at this meeting.

COMPARISON OF H^{∞}-OPTIMAL FEEDBACK CONTROL SYSTEM DESIGN METHODS

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SUMMARY

In the last few years there is a growing interest in the design of robust controllers. An optimal robust controller for a linear feedback system can be found by solving an H^{∞}-optimization problem.

In this lecture we will firstly discuss a way to formulate such an optimization problem. After that, we will compare solution methods for solving this problem. From some simple examples we will try to summarize computational methods by:

Kwakernaak ([1], [2])	: polynomial approach,
Safonov cs, Glover ([3], [4])	: Hankelnorm approximation,
Francis and Zames ([5])	: H^{∞}-interpolation theory,
Francis, Helton and Zames ([6])	: geometric approach,
Chang and Pearson ([7])	: Nevanlinna-Pick theory.

Finally, we will pay attention to numerical aspects of these methods.

[1] Kwakernaak, Minimax Frequency Domain Performance and Robustness Optimization of Linear Feedback Systems, IEEE Trans. Aut. Contr., pp. 994-1004, 1985.

[2] Kwakernaak, A Polynomial Approach to Minimax Frequency Domain Optimization of Multivariable Feedback Systems, Memorandum nr. 529, Dept. of Applied Math., Twente University of Technology.

[3] Safonov and Verma, L^{∞}-Optimization and Hankel Approximation, IEEE Trans. Aut. Contr., pp. 279-280, 1985.

[4] Glover, All Optimal Hankel-norm Approximations of Linear Multivariable Systems and their L^{∞}-error Bounds, Int. J. Contr., pp. 1115-1193, 1984.

[5] Francis and Zames, On H^{∞}-optimal Sensitivity Theory for SISO Feedback Systems, IEEE Trans. Aut. Contr., pp. 9-16, 1984.

[6] Francis, Helton and Zames, H^{∞}-Optimal Feedback Controllers for Linear Multivariable Systems, IEEE Trans. Aut. Contr., pp. 888-900, 1980.

[7] Chang and Pearson, Optimal Disturbance Reduction in Linear Multivariable Systems, IEEE Trans. Aut. Contr., pp. 880-887, 1985.

CONTROL ASPECTS OF NETWORKS OF QUEUES

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SUMMARY

1. Introduction

In the first part of this minicourse, networks of queues have been described and analyzed using countable state space Markov processes. On the basis of the equilibrium distribution for these processes one can achieve an open-loop, off-line, optimal design of the network, i.e. one designs a minimum cost network with acceptable performance under normal operating conditions. Due to the randomness of the load and due to possible equipment breakdowns, performance may still, at some instants, become unacceptable. Then a real-time, on-line, controller has to modify some system parameters, on the basis of measurements of the state of the systems. As illustrations we will discuss models for routing messages (customers) via state dependent alternate paths, as well as models for controlling the inflow of customers in packet switching (computer) and circuit switching (telephone) networks.

The talk will illustrate how classical ideas from systems and control theory are useful in designing good on line controllers. Among these, the value of information (measurements) for optimal control, the robustness and stability problems when different control loops interact and the reduction of the model size via decomposition in fast and slow subsystems.

2. Aggregation

To analyze the performance of a feedback controller one has to study the transient behaviour of a system. For queueing networks this is usually infeasible due to the large number of states. More tractable models are obtained via aggregation in nearly completely decomposable systems (Courtois [1], Gelenbe-Mitrami [2]) similar to electrical Norton equivalents and via diffusion approximations (Reiman [3]). Each of these techniques is based on a separation of fast and slow time scales. Fast and slow subsystems are obtained. Via aggregation most on-line control problems can be reduced to one of the following typical models.

3. Optimal control

Routing problems are described by the assignment of an arriving customer to one of several alternative servers. It will be shown that taking the workload of each server at the arrival time into account can significantly improve the performance (reduce average delay) over a predetermined assignment policy (Stidham [4], Ephremides et al.[5], Foschini and Salz [6]).

When there are different types of customers the sequence of giving service on one server is a well known problem(contention resolution). Various state dependent priority rules have been studied(Baras et al.[7], Varaiya et al [8]).

4. Stability and robustness

A third paradigmatic system is the case where the service rate decreases as the load-the queue length-increases. This happens e.g. when a series connection of servers and finite buffers is aggregated to a single server, as in models of virtual circuits in packet switching networks, or models of multiprocessing CPU's with paging. Various controllers have been analyzed, which refuse admission when the total number of customers present is too large , under names such as window policy (Lazar [9], Schwartz [10]), the knee criterion (Denning et al. [11]) etc. These are forms of output feedback. Stidham [4] has shown that state feedback can significantly improve the performance.

One well-known advantage of feedback controls is that systems can be designed more cheaply because the "variance reducing property" of the feedback loop makes it possible to work closer to the performance limit. This is true for queueing networks as well. However it also means that a small change of the parameters may cause a significant deterioration of the performance. This lack of robustness can be interpreted as the existence of one desirable and one undesirable locally stable equilibrium point of a nonlinear system. The ALOHA communication channel (Fayolle et al. [12]) will be used to illustrate this phenomenon.

This robustness problem becomes especially serious when various control loops interact. Changes in one loop may cause other loops to move from the desirable operating point to the undesirable equilibrium point. Krupp [13] has analyzed and simulated this for a simple three-node telephone network. Akinpelu [14] shows that for larger networks this problem becomes less serious, but nevertheless does still exist. There one considers one controller assigning call requests to alternate paths for each source destination pair. These controllers interact because they use common resources, the same communication channels. The only way to design a truly stable and robust system is to use global information on the state of the whole network in each local controller (Jaffe [15]). This however is practically not feasible; various heuristic approximations have been suggested.

References

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12. G. Fayolle, E. Gelenbe and J.Labetoulle: Stability and optimal control of the packet switching broadcast channel; Journal of the ACM, 24, pp.375-386, 1977.
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COMPARISON OF SOME PARTIAL DIFFERENTIAL MODELS OF FLEXIBLE STRUCTURES

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SUMMARY

In the literature several types of partial differential equation models have been proposed for large flexible structures. Once one has such a model then there are several theories for designing controllers to achieve various objectives. The weakness of this line of research as regards applications to the control of large flexible space structures is that no one is sure which type of pde model is appropriate and even if this were the case, in practice even the estimation of the modes is very approximate, especially for the higher frequencies. This is of course a common phenomenon in Control Engineering and there is a large body of theory devoted to this robustness aspect of controller design. In particular, Curtain and Glover in [1] have developed a theory for the robust stabilization of infinite dimensional systems. The idea is that if the nominal system has a transfer function $G_0(s)$ then one seeks to design a robust controller such that it also stabilizes a system with a transfer function $G(s)$ such that $\|G(s) - G_0(s)\|_\infty < \epsilon$; ϵ gives a measure of the robustness. This is a frequency domain approach and we try here to understand the implications of this theory for large flexible structures modelled by partial differential equations.

First we consider three pde models for flexible beams with different types of damping:

1. Euler-Bernoulli with structural damping.
2. Euler-Bernoulli with viscous damping.
3. Two beams connected through a point mass.

The beams in 1-3 are assumed to have free ends. In addition, we allow the models 1-3 to depend on certain parameters. We then systematically compare the differences $\|G_i(s) - G_j(s)\|_\infty$ for the different types of models 1-3, with different choices of parameters. This is interesting in itself, as we can compare quantitatively the influences of structural versus parameter variations for these pde models.

With the above data we can apply the theory of [1] to draw conclusions about the robustness of controllers based on a nominal pde model of type 1, 2 or 3.

The aim of this study is to give some insight in the robustness to model uncertainties of controllers designed on a nominal pde model.

1. R.F. Curtain and K. Glover. Robust Stabilization by finite dimensional controllers, Report CUED/F-CAMS/252, 1985, Engineering Dept, University of Cambridge, UK.

ON THE FACTORIZATION OF ROW-COLUMN-REDUCED POLYNOMIAL MATRICES

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SUMMARY

Row-column-reduced (r.c.r.) polynomial matrices have been used to study the absence of impulsive behavior in linear multivariable systems having a polynomial matrix system description (PMD), [1, sec. 3.3 and 3.4]. Row-column-reducedness is a straightforward generalization of column-reducedness and row-reducedness, [3], [4]. We report, [5], how the factor extraction techniques of [2, sec.II and III] highlight the properties of a r.c.r. polynomial matrix : i) any polynomial matrix $D(s)$ can be made r.c.r. by elementary polynomial operations upon D using a method similar to [3, pp. 27-28]; ii) any r.c.r. polynomial matrix $D(s)$ factorizes as $D(s) = D_{\ell}(s) \, . \, D_r(s)$ where the polynomial matrices $D_{\ell}(s)$ and $D_r(s)$ are resp. row-reduced and column-reduced. As a dividend we characterize the product factorization of a rational transfer function matrix (in right-left matrix-fraction form) as a product of two proper rational transfer matrices.

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NONLINEAR PROGRAMMING, EXACT PENALTY FUNCTIONS AND PROJECTION TECHNIQUES FOR NON-SMOOTH FUNCTIONS

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SUMMARY

We present a personal overview of various approaches to solving nonlinear programs with nonlinear constraints that make use of the l_1 exact penalty function.

The advantages, disadvantages and related remaining difficulties of these approaches will be considered. Finally some recent research and extensions will be mentioned.

ON NUMERICAL METHODS FOR CONTINUOUS LOCATION PROBLEMS, INCLUDING THE HANDLING OF DEGENERACY

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SUMMARY

Continuous location problems are potentially difficult to solve because the objective function is not every where differentiable. An algorithm based upon the solution of a finite sequence of linearly constrained subproblems is presented. Descent directions for these subproblems are obtained by projecting the Newton direction onto the corresponding constraint manifold. Univariate minimization is achieved via a specialised linesearch which recognises the possibility of first derivative discontinuity (and second derivative unboundedness) at points along the descent direction.

The algorithm extends earlier results of the authors and relates to methods recently described by Overton and Dax. In particular, it is known that degeneracy complicates the numerical solution of location problems. This degeneracy is identified and a method that circumvents the degeneracy is included.

An implementation of the algorithm that exploits the intrinsic structure of of the problem is described along with a discussion of numerical results.

NEW DEVELOPMENTS IN FACILITY LOCATION THEORY

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SUMMARY

The k-median problem has been widely studied both from the theoretical point of view and for its applications. An interesting theoretical development was the successful probabilistic analysis of several heuristics for this problem (e.g. Fischer-Hochbaum and Papadimitriou). On the other hand, the literature abounds in exact algorithms. Most are based on the solution of the so-called strong linear programming relaxation of the problem, which was found to yield impressively tight bounds compared to what can usually be expected in integer programming. In joint work with Sang Ahn and Alan Freize, we performed a probabilistic analysis of the strong linear programming relaxation under four classical models in location theory: the Euclidean, network, tree and "uniform cost" models. For example, for the Euclidean model with n points uniformly distributed in a square and $\omega<k<n/(\omega \log n)$ where $\omega \mapsto \infty$ as $n \mapsto \infty$, we show that the value of the relaxation is almost surely .99716... times the optimum k-median value. In other words, the error made by using the relaxation is almost surely less than one third of one percent. We also show that, under various assumptions, branch and bound algorithms that use this relaxation as a bound must almost surely expand an exponential number of nodes to solve the k-median problem to optimality. We report extensive computational experiments.

The Capacitated Plant Location Problem (CPLP) is often considered to be significantly harder than the the Simple Plant Location Problem (SPLP). The reason usually given is that "duality gaps" are larger. In collaboration with Sridharan, we started a thorough investigation of the duality gaps arising from various relaxations. The CPLP can be stated as

$$\text{Min } \Sigma_i \Sigma_j c_{ij} x_{ij} + \Sigma_j f_j y_j$$

$$\Sigma_j x_{ij} = 1 \text{ for all } i$$

$$\Sigma_i d_i x_{ij} \leqslant s_j y_j \text{ for all } j$$

$$\Sigma_j s_j y_j \geqslant \Sigma_i d_i$$

$$0 \leqslant x_{ij} \leqslant y_j \leqslant 1 \text{ for all } i \text{ and } j$$

$$y_j = 0 \text{ or } 1 \text{ for all } j.$$

We can show that, for the Euclidean model and under probabilistic assumptions similar to those made above, the relative error made by using the linear programming relaxation is almost surely the same for CPLP and SPLP. This analysis renders the statements on the comparative difficulty of CPLP and SPLP all the more intriguing. We also provide extensive computational experience.

TWO ALGORITHMS FOR WEIGHTED MATROID INTERSECTION

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SUMMARY

Given two matroids on the same ground set, a k-intersection is a set of cardinality k which is independent in both matroids. Given a weighting of the elements, we consider the problem of finding a maximum-weight k-intersection, if one exists. We discuss a new algorithm for this problem, obtained in joint work with Carl Brezovec and Fred Glover. This algorithm operates in a "horizontal" fashion. It starts with a k-intersection I. The set I is used to construct a digraph related to Glover's state graphs and Lawler's border graph. We then use negative length dicycles in our digraph to find an improved k-intersection. The procedure is repeated until an optimum is found. This horizontal approach, in conjunction with the introduction of artificial elements, yields a second algorithm. It has conplexity $O(nk(k+\log n+c))$, where n is the cardinality of the ground set and c is the complexity of the following circuit recognition problem: given a k-intersection I and $e \notin I$, find a circuit of $I+e$ or show that none exists, in each of the two matroids. Our second algorithm also solves the classical weighted matroid intersection problem and provides new simple proofs of the validity of classical matroid intersection algorithms.

THE USE OF NON-CONVENTIAL MATRIX CALCULUS IN LINEAR SYSTEM THEORY

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SUMMARY

In this talk, first some 'unconventional' matrix products will be defined. The properties of the Kronecker and the Khatri-Rao product, which is the Kronecker product columnwise, are investigated. Some 'mixed product' rules between these products and the 'conventional' matrix product are established. Special attention is paid to some theorems that clarify the relation between these matrixproducts and the eigenvalue and singular value decomposition.

These results are then used to demonstrate the analysis of the solution of linear matrix equations (Sylvester, Lyapunov, ...)

In a second part of the talk, the 'non-conventional' matrix calculus serves as a tool in the analysis of the structure of finite (block)Hankelmatrices of finite rank, containing the Markovparameters of a (multivariable) linear system. These results are easily extended to infinite (block)Hankelmatrices of finite rank. Some original theorems that clarify the relation between the structure of the Hankelmatrices and their singular value decomposition are established. For instance, it is proven explicitely that the singular values of any Hankelmatrix are determined uniquely by the knowledge of the singular vectors only. As an important result, a parametrisation is obtained of all finite (block)Hankel-matrices of finite rank, corresponding to a given set of eigenvalues of the systemmatrix.

Some preliminary ideas of the use of this parametrization in the context of noise cancellation in a realization problem (KUN) and of model reduction for 'exact' data will be developped. The relation with some novel approaches (VER) will be demonstrated.

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ON THE SET OF OBTAINABLE REFERENCE TRAJECTORIES USING MINIMUM VARIANCE CONTROL

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SUMMARY

In this talk we shall consider three quadratic cost criteria. We shall argue that the controllers resulting from two of these criteria are, from a practical point of view, not suitable for economic regulation.

The controller that in simulation results exhibits the best properties proves to be the Minimum Variance controller. For that reason the stabilization properties of this controller are investigated in more detail. We shall investigate the set of reference trajectories that can be tracked when the Minimum Variance controller is used. A necessary condition on the behaviour of a reference trajectory in order to belong to this set will be deduced. For time-invariant systems we can even give an exact characterization of the trackable reference trajectories.

The effect on the ability to track a certain reference trajectory, using restricted control, will also be discussed. The system analyzed is supposed to be linear, finite dimensional and discrete time.

SYSTEM IDENTIFICATION USING CANONICAL FORMS AND OVERLAPPING MODELS

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SUMMARY

Some properties of a class of multivariable input-output canonical forms that directly exhibit the system structure will be first considered. The use of such models in the identification of dynamical processes on the basis of generic noisy input-output sequences and the associated problem of the choice of the model structure will be then discussed. Final considerations will regard the possible advantages associated to the use of the wider class of overlapping models.

APPLICATION OF IDENTIFICATION TECHNIQUES TO THE MANAGEMENT OF NATURAL RESOURCES

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SUMMARY

This lecture describes some recent results obtained in two applications of identification techniques to natural processes that are currently being performed at Bologna University. Such applications regard:

I. IDENTIFICATION OF NATURAL GAS RESERVOIRS

A proper management of natural gas reservoirs is important both in the phase of primary production and after the conversion to storage operations. Such a management requires a dynamical model of the process to obtain an accurate prevision of the reservoir mean pressure under assumed injection/production schedules. The problems associated to the determination of such models will be discussed and the results obtained in the identification of an Italian gas reservoir presented.

II. IDENTIFICATION OF DYNAMICAL MODELS FOR DIATOM AND DINOFLAGELLATE BLOOMS IN THE NORTH-WESTERN ADRIATIC SEA

Algae blooms in the Adriatic sea have been observed since the last century. Today the quality of the sea water is monitored in several stations so that sequences of data regarding the blooms of different algae species, the physical status of the water and the presence of nutrients ($P\text{-}PO_4$, $N\text{-}NH_3$, $N\text{-}NO_3$, etc.) are available. The complexity of the involved phenomena has suggested to use an identification approach in the determination of the factors more strictly related to the blooms and in the estimation of dynamical models to be used for previsional purposes. The first results obtained in the application of this scheme to data regarding diatom and dinoflagellate blooms will be presented.

FINITE TIME SYSTEMS

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SUMMARY

A dynamical system is defined by $\Sigma := \{T, W, \mathbf{B}\}$, where $T \subset \mathbb{R}$ the time set, W the signal space, $\mathbf{B} \subset W^T$ the behaviour. A finite time system is a dynamical system with T a finite set.

Let $\mathbb{N} := \{1,2,\ldots\}$, and for $t_1, t_2 \in \mathbb{N}$, $t_1 \leqq t_2$, $[t_1,t_2] := \{t \in \mathbb{N};\ t_1 \leqq t \leqq t_2\}$. Let $W := \mathbb{R}^q$, $T_0 \in \mathbb{N}$ fixed, $T := [1,T_0]$. We define the class $\underline{\mathbb{B}}$ of linear shift invariant finite time systems as follows.

$$\underline{\mathbb{B}} := \{\mathbf{B} \subset (\mathbb{R}^q)^T;\ \mathbf{B} \text{ linear},\ \mathbf{B}|_{[2,T_0]} \subset \mathbf{B}|_{[1,T_0-1]}\}$$

We will concentrate on the data modelling problem, in which we have an observation $w \in (\mathbb{R}^q)^T$ and we have to choose a model $\mathbf{B} \in \underline{\mathbb{B}}$ to explain w. We will restrict attention to the exact modelling problem, i.e. one requires $w \in \mathbf{B}$.

In solving this modelling problem, the following concepts play a crucial role:

* complexity of a model
* corroboration of a model by data

Giving concrete specifications of these concepts, we will illustrate the modelling problem by solving, for $q = 1$, the problem of determining for given data the least complex exact model in the class of corroborable models.

Among other things, this will cast new light on the partial realization problem.

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REVERSIBILITY AND PRODUCT-FORM SOLUTION IN QUEUEING NETWORKS

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SUMMARY

An introduction to networks of queues will be given. For a class of networks the numbers of jobs at the various nodes are (quasi-) independent. This phenomenon and related properties are illustrated by reversibility concepts.

TIME-OPTIMAL CONTROL OF A ROBOT USING TIME-VARYING SWITHCHING LINES

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SUMMARY

The paper provides an answer to the question of how to drive a highly nonlinear, coupled system like a manipulator from an initial position in minimum time onto a (moving) target position.
As far as the optimal control problem is concerned, all classical solutions failed to provide a real time feedback solution. They all require the solution of a two point boundary value problem involving a considerable number of highly nonlinear differential equations. In an attempt to find at least a sub-optimal feedback solution, the phase plane techniques proved to be sufficiently strong. In general, the variable parameters are selected as phase variables and the constant parameters as those determining the shape of the switching line. In this study the classical phase plane techniques were modified to result in the so-called "time varying switching line". The variables to be controlled were selected as phase variables and others as parameters which determine the shape of the switching lines. In complex nonlinear problems these parameters also change. This resulted in a switching line that changes with time. The best control input is found by considering the most recent form of the switching line. Examples will be presented as strong evidences of the success of the techniques.
In controlling the manipulator, the state equations were uncoupled using a transformation. The transformation was obtained assuming the inertia matrix to be constant, but was updated using the current values at every sampling. In some cases, for example, when the system gets monotonously heavier the transformation was not successful. This could be overcome by using a heavier version of the system which is called an overestimated system, to obtain a good transformation. It was shown that these overestimates do not have to be exact and the optimal times do not show marked differences. Another observation made during the study is the existence of a sliding mode.
The method explained in this study requires the manipulation of a few algebraic equations to obtain the switching lines whereas Pontryagin's method required the solution of highly nonlinear coupled differential equations, where the boundary conditions are split. This in turn reduces the computational burden, thereby qualifying it as an efficient real-time solution. Since this is a feedback controller no accurate modeling is necessary and the extension of the solution into any number of degrees of freedom is straightforward.

MODIFIED DISCRETE-TIME COMPUTED TORQUE METHODS FOR HIGH PRECISION ROBOT CONTROL

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SUMMARY

A discrete-time formulation of the computed torque method is described. Application of this control algorithm to a simulation of the first 3 joints of a PUMA 600 robot illustrates the trajectory tracking performances.
These first results are compared with the performances of some modified versions of the classical computed torque method. Introduction of an integral action is shown to improve significantly the precision in trajectory tracking.
However, such performances can be strongly damaged in the presence of parameter identification errors in the decoupling compensator. Therefore an adaptive control algorithm based on the computed torque method is introduced. This yields an increase in robustness of the closed-loop system, as shown experimentally. The new adaptive control algorithm performs better than the classical adaptive pole-placement algorithm. This is due to the introduction of the desired joint velocities and accelerations in the control law, and to a velocity feedback.

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IMPACT OF ELASTICITY EFFECTS ON SPACE-MANIPULATOR CONTROL SYSTEM DESIGN

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SUMMARY

During operations with space-manipulators, the end-effector is required to follow a desired path with a certain accuracy. Deviations of this path due to inertial coupling and/or interaction of elasticity effects are to be expected.
We have the objective to study these elasticity effects and their impact on the design of the control system of the Service Manipulator System, the SMS, a space-manipulator defined by the European Space Technology Centre (ESTEC).

The SMS has an arm with six links and six rotational joints, having a reach of nearly 7 meters. It is to handle payloads up to 1500 kg, each joint being actuated by a DC-motor coupled to a gearbox.
Based on the preliminary design specifications, the model of the SMS, as used in this study, focusses on two items:

- the model of the joint actuators
- modelling of link elasticity

Of both models, the important dynamic characteristics will be discussed. As well, the models allow for analytical calculation of the displacement of the end-effector, due to elasticity either in the actuators or in the links.

To suppress the effects of inertial coupling and interaction of elasticity effects, two types of control strategies are studied:

- an independent joint control strategy
- a decoupling control strategy

The independent strategy is based on a single actuator model. It provides improved damping of the vibrations caused by gearbox elasticity, by using feedback of the actuator states.
The decoupling strategy however, using cross-joint feedback, is based on a configuration with three actuators coupled to three rigid links. It is superimposed to the independent control strategy, and suppresses effects of inertial coupling.

Computer simulations are used for the purpose of verification. Simulations with the Dynamic Control and Analysis Package (DCAP) show the 3-dimensional motion of the end-effector of the SMS. Also, the effects of gearbox elasticity and inertial coupling can be shown.

ON THE PARAMETER ESTIMATION OF THE RESPIRATORY CONTROL SYSTEM

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SUMMARY

In a living organism carbon dioxide is one of the main waste products of the metabolism. It is removed by the lungs via the ventilation. To keep the level of CO2 in the blood relatively constant, the ventilation is regulated by a respiratory controller. A commonly used model describing the ventilatory response to step changes in carbon dioxide (keeping the O2 level constant) consists of two parallel first-order systems with time delays (1). In preliminary studies this model was used to analyze the data of experiments on anaesthetized cats, using a least-squares procedure to minimize the output error (2). It turned out that in general the residual function was non-white; so serious doubt arose about the validity of the estimated parameters.
In the present study we modelled the noise in three ways: measurement white noise with and without process noise and measurement first-order coulored noise. To this end the models were formulated in the innovation form (3). A computer program was developed suitable to handle non equal sampled data, using Kalman filtering techniques, minimizing a one step prediction error. The time delays were estimated by a "grid search". This program has extensively been tested on simulated data (4). The test results gave good confidence in the variance of the estimated parameters. As expected the variances of the parameters were grossly underestimated if simulated data with coulored noise were fitted with a model assuming only white measurement noise.
The program has been used with data of real experiments. Results of parameter estimation will be illustrated with data of a cat before and after the administration of almitrine bismesylate, i.e. a new respiratory stimulant.
We conclude that modern parameter estimation techniques constitute a powerful tool in the study of the control of breathing.

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IDENTIFICATION OF A SPATIALLY VARYING PARAMETER IN A TIME-PERIODIC PARABOLIC SYSTEM

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SUMMARY

The estimation of a spatially varying parameter in a time-periodic boundary-value parabolic system is considered. We show that the parameter can be identified in the corresponding initial boundary-value problem. The minimization of the output least square criterion via the adjoint state method is implemented (using the "discrete" gradient). Numerical experiments are presented on a problem taken from oceanography : the identification of the CO_2 turbulent diffusion coefficient in a column of water. Cubic spline approximations of the parameter are tested on different sets of data.

COMPLICATED DYNAMICS IN SIMPLE PROCESSES

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SUMMARY

One can use the methods developed in [2]to study the dynamics of the map defined by the Newton algorithm for finding the real zeros of a function.

It is known that complicated dynamics must arise when Newton's method is applied to every map that has at least three simple real zeros, see e.g. [1], [3] and [4].

For a suitable class of functions, it will be discussed that the Newton method produces bounded solutions which will not converge for a set of initial values having positive Lebesque measure.

Further, it will be argued that the qualitative dynamical behaviour of the map defined by the Newton algorithm can be analyzed explicitly for functions in the suitable class. Finally, it will be discussed that this qualitative dynamical behaviour is persistent under small smooth perturbations.

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SOME RESULTS ON THE MINIMAL REALIZATION OF DISCRETE-EVENT DYNAMIC SYSTEMS

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SUMMARY

Many phenomena are modelled as linear systems, since linearity is a most tractable property. Many problems, however, for instance in optimization on networks, machine scheduling, discrete-event processes or related to Petri-nets, are nonlinear in the conventional arithmetic but are linear in the so-called max-algebra, also called path-algebra or diod. The elements in the max-algebra are the real numbers (and minus infinity) and the admissible operations are maximization and addition.

In [2] an analogy between the conventional linear system theory [1] and discrete-event systems is developed. The notions of eigenvalue and eigenvectors in the max-algebra sense play an important rôle. In [4] a beginning has been made with the realization of a discrete-event system (in state space notation) if the transfer matrix was given.

In the current paper it is investigated whether the conventional minimal realization theory [1] can be converted to the theory of discrete-event systems. Minimal realizations are important for compact mathematical descriptions without dimensional redundancies and also for design purposes [2]. We restrict ourselves to single input/single output systems. It turns out that the characteristic equation of a (square) matrix in the max-algebra plays a crucial rôle. Unlike the situation in ordinary matrix theory where every monic polynomial is a characteristic polynomial of a suitably chosen matrix, in the max-algebra not always a matrix can be found such that its characteristic equation coincides with a given polynomial equation. The theorem of Cayley-Hamilton in the max-algebra [3] could be used to prove some partial results.

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STATE DEPENDENT ROUTING OF TELEPHONE TRAFFIC AND THE USE OF SEPARABLE ROUTING SCHEMES

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SUMMARY

In routing of (circuit switched) telephone traffic for every telephone call offered to the system, a decision must be made, in the first place on whether to accept (route) the call or to block (refuse) it, in the second place, if the call is accepted, on which route to use for the call.

The outcome of the decision always depends on the state of the network (numbers of busy and idle trunks in various trunk groups). In older schemes the decision only depends on which trunk groups still have idle trunks. In modern, so called State Dependent schemes, the decision depends on the actual numbers of busy and idle trunks in the various trunk groups.

This talk consists of three parts:

First, I will give a short historic overview of the problem of optimal routing of (circuit switched) telephone traffic, including a description of hierarchical routing schemes and the first Dynamic Non-Hierarchical Routing (DNHR) scheme.

Second, I will discuss the formulation on the optimal State Dependent Routing problem as a Markov Decision problem. It will be seen that this Markov Decision formulation leads to a State Space of astronomical size (easily $> 10^{200}$ states) and thus, in the first place, is unsolvable and, in the second place even if solved leads to unimplementable policies.

Third, I will introduce the class of so called separable routing schemes. Some open problems in finding the optimal Separable Routing Scheme will also be discussed.

A separable routing scheme is a routing scheme where the (state dependent) pretended desirability of a route is a simple separable (additive) function of the states of the individual trunkgroups in that route. In particular, the desirability of a route is pretended to be independent of the states of trunkgroups not in the route. I will show that these separable schemes are implementable and I will give evidence, both from theoretical analysis and from simulation, that it is possible to construct separable routing schemes with extremely good performance.

NUMERICAL METHODS FOR THE SINGLE SERVER QUEUE

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SUMMARY

The structure of the single server GI/G/1 queue will be explained and several methods to obtain numerical information about the stationary distribution will be discussed. Among these methods are the Wiener Hopf Factorization and the Phase Type Method started by Neuts and recently brought to full maturity by Ramaswami and Lucantoni.

A method called the "Almost Phase Type Method," which is related to both Wiener Hopf Factorization and to the Phase Type Method, will be discussed in more detail. This method is based on the idea of counting phases. As such, precursors of this method received attention by Luchak, Schassberger, Shantikumar, and others.

Algorithms based on the "Almost Phase Type Method" and numerical results obtained by those algorithms will be presented.

DESIGN OF AN OPTIMAL VISION-BASED CLASSIFICATION SYSTEM FOR ROBOTS

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SUMMARY

For a vision system in control applications in a production plant different fields can be distinguished, two of the most important being:

1. Recognition of different parts which are to be assembled by a robot. In general the objects to be recognised differ substantially so that rather simple features can be used.

2. Product inspection after completion of the production process. Here the objects have to meet certain specifications and the vision system is used to detect those parts which are out of tolerance.

In this paper attention will be focussed on the first item, where not only a high classification performance but also other aspects need to be considered, such as speed of recognition.
Particularly it has been studied what results can be achieved if the design of the classifier is controlled by a multicriterion function incorporating the most important aspects, i.e. the classification performance, the reject rate and the speed of recognition. For this purpose a classification strategy and a statistical classification model have been derived. This has resulted in a multistage classification system which is optimised in a supervised learning mode.

Experiments have been carried out at various low resolutions of the camera image. These experiments have shown that the optimisation as described here leads to a substantial improvement in the system's total performance.

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A note on the structure of two subsets of the parameter space in adaptive control problems

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SUMMARY.
Consider the following class of systems:

$$x_{k+1}=Ax_k+Bu_k,\ \ (A,B)\in\mathbb{R}^{n\times n}\times\mathbb{R}^{n\times m},$$

and let for each (A,B) a control law $F(A,B)\in\mathbb{R}^{m\times n}$ be given such that the closed loop system $x_{k+1}=(A+BF(A,B))x_k$ acts "satisfactorily". Suppose now that a plant is represented by some (A_0,B_0) which is unknown but fixed. We will study some consequences of the use of an indirect adaptive control algorithm based on certainty-equivalence. In such a scheme at every time instant an estimation $(\hat{A}_k,\hat{B}_k)$ is made of (A_0,B_0) on the basis of the observed data and then $F(A_0,B_0)$ is applied, and after the new data has become available a new estimation is made etc. The problem we want to study is independent of the estimation procedure hence we will assume that $(\hat{A}_k,\hat{B}_k)$ is available for all k. A most desirable property of an algorithm is obviously that $F(\hat{A}_k,\hat{B}_k)$ converges to $F(A_0,B_0)$, however since identification takes place in closed loop this might be difficult to achieve. To be more precise, define the following sets:

$$H:=\{(A,B)\ |\ F(A,B)=F(A_0,B_0)\ \}$$

$$G:=\{(A,B)\ |\ A+BF(A,B)=A_0+B_0F(A,B)\ \}$$

It will be explained that G is the smallest invariant subset of the parameter space i.e. G consists of possible limit points, whereas H could be seen as the set of desirable limit points. We will study the sets G and H for the case F is defined by a quadratic cost criterion. It will be shown that G and H are manifolds, and that their intersection consists of nothing more then the the "true" parameter (A_0,B_0). This means that the only invariant point in the parameter space which corresponds to optimal control is the one which represents the true system.

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A THEORETIC SYSTEM APPROACH OF TIMED DISCRETE EVENT SYSTEMS

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SUMMARY

The absorbing semi-field ($\mathbb{R}$, max, +) is the natural algebra we can develop a linear theory of such systems.

Its power of modelization is equivalent to the timed Petri-net one.

In the special case of decision free Petri-net, efficient manipulations of transfer fucntions can be done.

We shall make a general presentation of this theory and of its power of modelization.

IDENTIFICATION AND CONTROL OF DIFFUSION PROCESSES: AN EXPERT SYSTEM

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SUMMARY

We describe the current state of an expert system designed for controlling stochastic processes.

The system will be able to make theoretical analysis of the model, to choose a method, to generate numerical programs, to make numerical experiments, to generate a report.

The architecture and the mathematical methods used will be explained.

Avoiding the development of congestion on a freeway : modelling and prediction of traffic flow.

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SUMMARY

In dense freeway traffic congestion frequently occurs while there seems to be no direct cause (an accident, a bottleneck e.g.). We would like to prevent such a congestion from occurring in order to increase the safety and improve the quality of the traffic flow. Our approach is based on the so called freeway control and signalling system installed on several freeways in the Netherlands (Delft-Rotterdam, Utrecht). This system consists of induction loops placed in the road surface and matrix signal boards above the road. The induction loops inform us about the actual traffic situation : the passing of cars is registrated and their speed is measured. The traffic may be 'controlled' by showing advisory speeds on the matrix boards.

Now the first step is to develop a model for the behaviour of the traffic. A model that is commonly used is the one derived by Payne [1]. The traffic stream is described by the quantities density (vehicles/km/lane) and mean speed (km/h). The stochastic version of this model was given by Van Maarseveen [2].

As a second step the model parameters have to be identified using real life data (given by the signalling system) or based on theoretical investigations. The model can then be simulated in order to check the validity of the model under various circumstances.

The last step consists of the derivation of one or more filter algorithms for the estimation of the state of traffic based on the measurements. These algorithms then have to be evaluated and the model or filter may have to be changed in order to improve the quality of the estimations.

In this lecture the traffic model is explained and some simulations are shown. Comments with regard to the model parameters are made. Possible filter algorithms are presented and their numerical implementation is discussed.

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PIECEWISE LINEAR ROBOT CONTROL

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SUMMARY

In general, a complete control system for a robot consists of several 'levels' of different 'intelligence'. The lowest control level (the level closest to the mechanism) contains the feedback control of the seperate servo motors or actuators. An often encoutered objective for such a feedback control is to decouple the robot dynamics in some given coordinates (configuration coordinates, Cartesian end-effector coordinates, etc.). In addition it is preferable that the closed loop system behavior be linear. If this is guaranteed, the higher control levels dealing with trajectory planning, obstacle avoidance etc. can concentrate solely on their proper tasks.

Several suggestions have been made to accomplish the above stated control objective. Computed torque schemes and resolved rate control are theoretically established methods, however they are derived from feed-forward ideas and hence rely heavily on accurate dynamical system models. If the actuator dynamics (often ommited in publications) are included into the model, the resulting control puts such a large computational burden on the controlling computer that implementation is usually not feasible.

In this paper, we present a computationally simple controller. The controller is a piecewise linear approximation of a unique nonlinear decoupling control law L which allows arbitrary pole placement of a smooth nonlinear system S. Linearization can either be done by linearizing the nonlinear control law L, or by first linearizing the nonlinear system S and then deriving the appropriate control laws L'. We show that both methods yield the same result, provided, of course, that the linearizations are performed at the same point in the state space. Hence linearizing and control synthesis are commutative operations here. Using this property one can transform the nonlinear control problem into a series of linear problems. In solving the linear problems, we obtain at a set of state dependant static precompensators and state feedback matrices. The controller interpolates and switches between these values and hence approximates the nonlinear control law.

Special attention is paid to the methods of interpolation. It is shown that the piecewise linear approximation of the nonlinear control must be at least continuous in the whole state space in order to avoid limit cycles and control chatter.

One of the principal advantages of this approach is the ease with which a decoupling controller can be derived for an arbitrary choice of output coordinates. The controller synthesis uses linear models, and implementation as well as on-line computing time are identical regardless of the coordinates in which the system is decoupled. This is not the case for a nonlinear decoupling controller.

The degree to which the resulting system behavior approximates a decoupled and linear behavior depends on:

a) the size of the intervals used in the piecewise linear approximation
b) the model inaccuracies
c) the robustness of the linear control laws L'

It is demonstrated by means of simulation that an existing hydraulic robot system can be controlled by means of a fairly inexpensive computer (.05 Mflop) and 1 to 10 Mbyte storage space. The remaining interaction (coupling) in the system is roughly one order of magnitude less than that of a conventionally controlled system, using siso control.

COLLISION AVOIDANCE OF AIRCRAFT: AN APPLICATION OF STOCHASTIC CONTROL THEORY

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SUMMARY

A study is made of a simple situation of collision avoidance encountered by Air Traffic Control, or, ATC for short. This is formulated as an impulse control problem and recent results in stochastic control theory are used for its solution. This leads to a quasi-variational inequality (QVI) and some modifications are made for numerically solving the QVI.

A very simple model is considered in this paper. The results are illustrated by simulation studies. Even this simple model leads to enormous numerical difficulties and the associated computational aspects are also discussed in detail.

FAMILIES OF LINEAR QUADRATIC PROBLEMS: CONTINUING PROPERTIES

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SUMMARY

The general linear quadratic problem consists of minimizing the performance index

$$J(x_0,u) = \int_0^\infty \| Cx(t) + Du(t) \|^2 \, dt$$

subject to

$$\dot{x}(t) = Ax(t) + Bu(t); \; x(0) = x_0; \; x(\infty) = 0.$$

It can be shown that the above problem yields for every initial condition x_0 a finite optimal performance $J^*(x_0)$ if and only if the pair (A,B) is stabilizable. Moreover, under the additional assumption that the system (A,B,C,D) has no invariant zeros on the imaginary axis, it may be shown that for every initial condition x_0 there exists an optimal control and optimal state trajectory, $u^*(x_0)$ and $x^*(x_0)$ respectively. As the above problem is posed in its full generality, these will in general be distributions. It can be proven that for every initial condition x_0 the optimal control and state trajectory are unique if and only if the system (A,B,C,D) is left-invertible.

In the present talk we will consider the situation that the above performance index depends on a real parameter, say $\lambda \in [0,1]$, i.e. that we require the minimization of

$$J_\lambda(x_0,u) = \int_0^\infty \| C(\lambda)x(t) + D(\lambda)u(t) \|^2 \, dt.$$

In this case the optimal performance $J_\lambda^*(x_0)$ and the optimal control $u_\lambda^*(x_0)$ and state trajectory $x_\lambda^*(x_0)$ depend on λ. We will adress the following questions:

(1) Under what conditions does the optimal performance $J_\lambda^*(x_0)$ for every initial condition x_0 depend continuously on λ?

(2) Assuming that for every λ the system $(A,B,C(\lambda),D(\lambda))$ is left-invertible (or equivalently: for every λ the optimal control and trajectory are unique for all x_0), under what conditions is the mapping

$$\lambda \to (x_\lambda^*(x_0), \; u_\lambda^*(x_0)),$$
$$[0,1] \to \mathcal{D}_+^{\prime n} \times \mathcal{D}_+^{\prime m}$$

a continuous mapping for every initial condition x_0?

A very interesting situation occurs if for some exceptional value $\lambda_0 \in [0,1]$ the system $(A,B,C(\lambda_0),D(\lambda_0))$ fails to be left-invertible. In that case $u^*_{\lambda_0}(x_0)$ and $x^*_{\lambda_0}(x_0)$ will no longer be unique and the following questions can be formulated:

(3) Do the limits $\lim\limits_{\lambda\to\lambda_0} x^*_\lambda(x_0)$ and $\lim\limits_{\lambda\to\lambda_0} u^*_\lambda(x_0)$ exist?

(4) If so, are these limits solutions to the linear quadratic problem associated with the system $(A,B,C(\lambda_0),D(\lambda_0))$?

(5) How can these limits be characterized in terms of the system $(A,B,C(\lambda_0),D(\lambda_0))$?

The questions posed above are mainly inspired by similar questions that have been studied before in the context of "cheap control". The latter problem requires the minimization of

$$J_\lambda(x_0,u) = \int_0^\infty \| Cx(t)\|^2 + \lambda^2\|u(t)\|^2 \, dt$$

and studies the situation that λ tends to zero, i.e. that the cost of control energy becomes small. Obviously, this is a special case of our more general set up and may be recovered by taking

$$C(\lambda) = \binom{C}{0} , \; D(\lambda) = \binom{0}{\lambda I} .$$

CONTINUOUS-TIME CONSTRAINED LEAST-SQUARES ALGORITHMS FOR RECURSIVE PARAMETER ESTIMATION OF STOCHASTIC LINEAR SYSTEMS BY A STABILIZED OUTPUT ERROR METHOD

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SUMMARY

This contribution is based on a report with the same title /1/ and deals with parameter estimation for continuous-time models /2/.

- A continuous-time version of the well-known recursive discrete-time least-squares algorithm for the estimation of parameters of continuous-time systems is presented. The algorithm is shown to minimize a quadratic functional representing a cost function in terms of the parameter error between the system and its model. The estimation is demonstrated to have exponential convergence properties. The error considered is a modification of the usual equation error /2/.
- The algorithm is then extended in order to handle equality constraints. The resulting algorithm is also shown to minimize a quadratic functional and to possess exponential convergence properties. By the use of a penalty function inequality constaints can also be treated.
- The constrained version of the algorithm is used in an output error scheme for parameter estimation. On applying this scheme to deterministic systems, the parameter error displays global convergence when the output error is filtered by an adjustable filter. The parameters of this filter are estimated by an extended parameter vector /3/.
- In stochastic systems, convergence is obtained when a transfer function associated with the adjustable filter parameters and the (unknown) system is strictly positive real /4/. This can be achieved using an algorithm with inequality constraints, where the filter parameters are confined to a closed set. Simulation shows this method to feasible.

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EQUATION ERROR AND OUTPUT ERROR METHODS IN MULTIVARIABLE PROCESS IDENTIFICATION; MODELS AND CRITERIA

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SUMMARY

When identifying a multivariable process the choice of a proper model set, its parametrization and the choice of the identification criterion are items that play a key role in determining the resulting model.
The identification criterion defines the way in which the original process is approximated by the model if the process under consideration is not contained in the chosen model set. The kind of approximation that is desired has to be dictated by the intended use of the model (simulation, prediction, controller design). Properties of both equation error and output error criteria will be demonstrated by means of the impulse response of the coresponding identified models.
A number of parametrizations will be discussed: canonical and pseudo-canonical state space models and matrix fraction descriptions, parametrization in Markov parameters. Special attention is given to a parametrization in Markov parameters together with coefficients of the minimal polynomial. The corresponding model set shows some interesting properties that will be demonstrated. Several model sets, used for output error and equation error minimization, are evaluated in view of their usefulness for simulation purposes.
A overview is given of the identification algorithms that are currently available in the authors' groups, incorporating least squares-, instrumental variable- and maximum likelihood techniques.
Results of applying these algorithms to a data set of an industrial process are given in a companion presentation [1].

[1] Ton Backx et.al: Equation error and output error methods in multivariable process identification; modelling of a glass tube production process.
To be presented at this meeting.

NONLINEAR CONTROL THEORY AND ROBOT MANIPULATOR CONTROL

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SUMMARY

The dynamical equations of motion of a kinematic chain (with revolute joints) are nonlinear and tightly coupled. Especially the centrifugal and Coriolis forces, which depend in a quadratic way on the generalized velocities, are of a complicated nature and cannot be neglected for high-speed, high-precision robots. It is therefore to be expected that nonlinear control theory may have something to say for robot manipulator control.
In this talk we will give an overview of some recent results of nonlinear (geometric) control theory which pertain to the manipulator case. Surprisingly, for the commonly considered case of rigid link manipulators the theory appears to be very simple, almost trivial, while already for robots with, say, two elastic joints the situation becomes very complicated. The immediate application of the theory for practical purposes is sincerely hampered by the fact that one usually needs precise knowledge of the state and parameters of the system. It will be argued that for developing a more robust control methodology, nonlinear control theory has to take into consideration the specific physical characteristics of the manipulator dynamics. Some, partly preliminary, ideas for doing this will be discussed.

DISTURBANCE DECOUPLING AND OUTPUT STABILIZATION BY MEASUREMENT FEEDBACK

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SUMMARY

In this talk we shall consider a synthesis problem that includes the disturbance decoupling problem and the problem of stabilizing the output with respect to the disturbances.
The linear time invariant system considered is given by the equations

$$\dot{x} = A\,x + B\,u + G_1 d_1 + G_2 d_2 ,$$
$$y = C\,x ,$$
$$z_1 = H_1 x \ , \ z_2 = H_2 x ,$$

where x is the state, u is the control, d_1, d_2 are unknown inputs, cq. disturbances, y is the measurement and z_1, z_2 are to-be-controlled outputs of the system.
The problem considered in this talk consists of finding a dynamic measurement feedback compensator, described by the equations

$$\dot{w} = K\,w + L\,y ,$$
$$u = M\,w + N\,y ,$$

where w is the state of the compensator, such that in the closed loop system the transfer function from the disturbance d_i to the to-be-controlled output z_j equals zero for (i,j)=(1,1),(1,2) and (2,1), while the transfer function from the disturbance d_2 to the to-be-controlled output z_2 is stable.

Conditions for the solvability of this problem are given in state space concepts as well as in frequency domain terms. Certain special cases of our problem shall also be discussed.

Stochastic realization and factor analysis

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SUMMARY

A general problem of science and engineering is to represent observations by a model. R.E. Kalman [1982,1983] has been voicing a critique of modeling in econometrics. His suggestion is to formulate this modeling problem as a realization problem of system theory.

For the representation of an observed random vector several models have been proposed. Some of these models are: the regression model, the errors-in-variables model, the factor analysis model and the confluence analysis model. Factor analysis has been introduced by the psychologist C. Spearman in 1904, generalized by L.L. Thurstone in 1931 and developed by psychologists and statisticians. Confluence analysis has been introduced by R. Frisch in 1934 and partly developed by O. Reiersøl. Econometricians such as T.C. Koopmans have considered these models but have apparently become bogged down by what they call the "identifiability" problem for these models. Yet there is still much to say for the factor analysis or confluence analysis model. The key property of this model is the conditional independence of the components of the observation vector given the factor. On the basis of this property one may define a rather general factor model.

In the presentation stochastic realization problems will be formulated for an observation vector in a nondynamic context. The questions in this problem are the existence of a factor model that represents the given observations and the classification of all minimal such models. Only a special case of these stochastic realization problems will be discussed in some detail.

In a dynamic context where an observed stochastic process has to be modeled, the criticism of econometrics leads to a stochastic realization problem for a Gaussian process. The problem is to represent an observed process such that the inherent causality relation is made explicit. Several classes of stochastic dynamic systems with which this may be done will be discussed.

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THE CONTROL OF AN ELECTRIC SERVO SYSTEM

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SUMMARY

In many cases a control system has to be designed after the constructive design of a mechanical system. In many of such cases the mechanical construction is heavy and stiff. Not always such a stiff mechanical system is needed for the application especially when the system is designed together with a control concept.

The control of the endposition of a beam is an example which is presented. The aim of the research is how to model such a system and above all how many modes have to be taken in account of the control design and what type of measurement is necessary.

First will be shown how the modal modelling approach of a flexible beam suits very well in the bondgraph concept of modelling. The several modes are represented by mass and compliance on second order systems. They are coupled by Transformers to the drive system. The transformation ratio's are depended on the boundaries of the beam. From this model is derived how the modes of interest can be measured by gauge strips. The angular control of the beam is based on the assumption that only the input angle and angular velocity of the beam can be measured.

These two quantities are input to a model of the beam from which the necessary states of the modes are estimated. These states are used in a state variable feedback of the overall system.

Results of simulation as well as from practical tests are shown.

MATHEMATICAL MODEL ORDER REDUCTION FOR THE CONTROL OF FLEXIBLE SPACECRAFT: A DISCUSSION OF APPROACHES

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SUMMARY

Increases in size and mechanical complexity of spacecraft result in increased complexity of the mathematical model of the spacecraft dynamics. In turn, this results in increased computational effort, increased difficulties in understanding the characteristics of the spacecraft dynamics, and increased difficulties in designing as well as implementing suitable algorithms for the control of the spacecraft dynamic motions. Reductio n of the order (i.e. the complexity) of the mathematical open loop model with minimal loss of model accuracy, is therefore of prime importance.

Literature contains descriptions of a large number of approaches towards open loop model order reduction. These have been surveyed from the point of view of usefulness for application to flexible spacecraft dynamics models. Six basic approaches have been identified, involving; (i) parameter optimization, (ii) aggregation, (iii) singular perturbation, (iv) modal dominance, (v) component cost analysis, and (vi) internal balancing, respectively. The latter three approaches appear to be most meaningful, and convenient in applications.

The problem of model order reduction is reviewed, and each of the six approaches is discussed. The latter three approaches are applied to the case of a long, flexible beam in space, controlled with two line torquers.

Keywords. Space vehicles; attitude control; vibration control; modelling; large-scale systems; system analysis; controllability; observability; control theory; system order reduction.

Reference. Mathematical models of flexible spacecraft dynamics: a survey of order reduction approaches.
P.Th.L.M. van Woerkom, National Aerospace Laboratory NLR, Amsterdam, The Netherlands, MP 85004 U, 1985.

NUMERICAL ANALYSIS OF QUEUEING NETWORKS

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SUMMARY

A short introduction is given in the numerical evaluation of separable queueing networks. Recent approaches to more efficient computation will be indicated.

It is demonstrated what type of numerical analysis is possible for non-separable networks of queues.

TRACTABLE MODES OF INTERACTION IN MULTI-COMPONENT SYSTEMS

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SUMMARY

If one can calculate the equilibrium distribution of a stochastic process then one has made valuable progress. However, even this is impossible for many processes which are of interest, and, in particular, for many processes representing a system of interacting components. Examples are given of some such systems for which the equilibrium distribution is nevertheless calculable. One example is that in which components interact by the passage of some kind of quantum or unit between them (e.g. statistical mechanics, Jackson networks of queues). Another example is that in which the components would be independent were it not that they all react with a common environmental variable. We shall consider the particular case of process in which departures from a group of individuals both are triggered by an 'excitation' variable and increease excitation. An example which falls into both categories is that of interaction between species mediated by competition for common resources. An examination of this process yields a stochastic version of the 'principle of competitive exclusion' and an extremal criterion for the species which will survive.

QUEUEING NETWORKS, COMMUNICATION NETWORKS AND OPTIMAL ROUTING

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SUMMARY

We consider networks of queues, and also communication networks of the circuit-switching variety, for which a call will be accepted only if (although not necessarily if) a complete route can be found for it. One can design a network which will cope optimally with a given traffic, subject to physical or economic constraints. This exercise generates certain cost concepts which may be useful for the *adaptive* (i.e. state-dependent) routing of traffic. The exercise also generates different concepts of an optimum: individual, social and bureaucratic.

THE GRAPH METRIC FOR SISO LINEAR DISTRIBUTED SYSTEMS

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SUMMARY

We present a generalization, [1], of Vidyasagar's graph metric for linear lumped systems, [2], to single input - single output (SISO) linear *distributed* systems, [3] - [4], where any real $\sigma_o \leqslant 0$ may be a stability margin (instead of $\sigma_o = 0$ only). We handle SISO distributed systems described by a transfer function of exponential order, i.e. in the framework summarized by the quadruple $(\hat{F}(\sigma_o)\ ,\ \hat{E}(\sigma_o)\ ,\ \hat{E}^{\infty}(\sigma_o)\ ,\ J_{\varepsilon\sigma_o})$, [4]; these results generalize to the more general framework $(\hat{B}(\sigma_o)\ ,\ \hat{A}_-(\sigma_o)\ ,\ \hat{A}_-^{\infty}(\sigma_o)\ ,\ J_{\sigma_o})$, [3]. First the *spectral factorization* problem for such systems is solved by using symbolic calculus in Banach algebras, [5]. This enables us then to get a well-defined concept of *normalized coprime fraction* for a system with transfer function $\hat{p}$ in $\hat{F}(\sigma_o)$ and to prove the existence of such fractions for any such $\hat{p}$, [1]. Next, with this new concept, we can define the *graph metric* for such SISO linear distributed systems and prove that its corresponding induced topology on $\hat{F}(\sigma_o) = [\hat{E}(\sigma_o)].[\hat{E}^{\infty}(\sigma_o)]^{-1}$ is the so-called graph topology, (the weakest one in which feedback stability is a robust property), [1] - [2].

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SOME INVARIANCE CONCEPTS FOR INFINITE DIMENSIONAL SYSTEMS

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SUMMARY

Let us consider the control process described by

1) $$\dot{x} = Ax + Bu \quad ; x \in \mathbf{H}, \; u \in \mathbf{U}$$
$$y = Cx \quad ; y \in \mathbf{Y}$$

where $\mathbf{H}$, $\mathbf{U}$ and $\mathbf{Y}$ are Hilbert spaces, B and D bounded operators from respectively $\mathbf{U}$ to $\mathbf{H}$ and $\mathbf{H}$ to $\mathbf{Y}$ and A generates a C_0 semigroup T(t).

A subspace $\mathbf{V}$ of $\mathbf{H}$ will be called (bounded) closed loop invariant if there exists a bounded feedback law F ; F: $\mathbf{H} \to \mathbf{U}$ such that $T_F(t)\, \mathbf{V} \subset \mathbf{V}$, where $T_F(t)$ is the semigroup generated by A + BF.

In this paper we will assume that A is the "heated rod" operator and B is one dimensional. We will ask ourself if the supremal closed loop invariant subspace contained in the kernel of C , $\mathbf{V}^*$(Ker C), exists. This question is completely solved by the next theorem.

Theorem 1

$\mathbf{V}^*$(Ker C) exists iff there exists a sequence in $\mathbb{N}$, denoted by n_k , such that

$$\sum_{k=1}^{\infty} \left| \frac{-n_k^2 - \mu_k}{b_{n_k}} \right|^2 < \infty \quad ;\text{where } b_{n_k} = \langle b, \sqrt{2}\cdot\sin(n_k^2)\pi^2 x \rangle =$$

$$= \int_0^1 \sqrt{2}\cdot b(x)\cdot\sin((n_k^2)\pi^2 x)\cdot dx$$

and μ_k is the k'th zero of the transfer function : $C(sI - A)^{-1}b$.

reference:
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TIME SCHEDULE

Time	Plenair	OR	SC1	SC2
Wednesday January 15, 1986				
11:25	Opening			
11:30	Whittle (1)			
12:30	Lunch break			
14:00			Van Woerkom	Meerwaldt
14:30			Bontsema	Udink ten Cate
15:00			Kuiper	Merckx
15:30	Tea break			
16:00		Cornuéjols (1)	Guidorzi (1)	
17:00		Conn (1)	Boekhoudt	Van den Hof
17:30		"	Polderman	Backx
18:00	End			
Thursday January 16, 1985				
09:00	J.P. Quadrat (1)			
10:00	Coffee break			
10:30	Minicourse (1)			
11:30		Conn (2)	Guidorzi (2)	
12:30	Lunch break			
14:00	Minicourse (2)			
15:00	Tea break			
15:30		Ott (1)	Olsder	Van der Woude
16:00		"	Nusse	Zwart
16:30		Whittle (2)	Heij	Winkin
17:00		"	Van Schuppen	
17:45	Vergadering			
Friday January 17, 1985				
09:00	Minicourse (3)			
10:00	Coffee break			
10:30		Cornuéjols (2)	Van der Schaft	Callier
11:00		"	Katupitiya	De Moor
11:30		Ott (2)	Van Vugt	Engwerda
12:00		"	Passenier	Trentelman
12:30	Lunch break			
13:30			Sperling	Ten Hove
14:00			Kinnaert	Smulders
14:30			Quadrat (2)	
15:30	Tea			