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WORKSHOP ON FEEDBACK AND SYNTHESIS OF LINEAR SYSTEMS

BIELEFELD, GERMANY, JUNE 22 - 26, 1981

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Abstract

The author participated in the workshop on feedback and synthesis of linear systems in Bielefeld, Germany, June 22 - 26, 1981. This report summarizes some of the experience from that workshop.

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Abstract

The author participated in the workshop on feedback and synthesis of linear systems in Bielefeld, Germany, June 22 - 26, 1981. This report summarizes some of the experience from that workshop.

Table of contents

1. Introduction

This report describes a "Joint workshop on feedback and synthesis of linear and nonlinear systems". The linear part of the workshop was held in Bielefeld, Germany, June 22 - 26, while the nonlinear part was held in Rome, Italy, June 29 - July 3, 1981. The workshop was organized by the "Forschungsschwerpunkt Dynamische Systeme, Universität Bremen, Germany" and "Instituto di Automatica, Universita di Roma, Italy." It was sponsored by these two institutes together with "Zentrum für Interdisziplinäre Forschung, Universität Bielefeld, Germany. The scientific committee concisted of D Hinrichsen (Bremen), A Isidori (Rome), A Krener (Davis), H F Münzner (Bremen) and D Prätzel-Wolters (Bremen).

I participated in the linear part in Bielefeld and this report describes that part. Section 2 contains a survey of some of the topics and papers and section 3 contains a schedule of speakers and subjects.

Acknowledgements

The financial support from the conference organizers and from Lund University is gratefully acknowledged.

2. A survey of some of the topics

In this section I will present some of the talks. The presentation is by no means complete and necessarily biased by my own knowledge and interests.

2.1 Problems connected to the infinite-frequency behavior of the system

Jan Willems considers systems, which are affected by disturbances and have different measured and controlled outputs, Dynamic feedback is allowed and the problem is to find conditions on the system so that the L_1-norm of H_{ez} (t) can be made arbitrarily small. Here H_{ez} (t) is the impulse response matrix from the disturbance to the controlled output of the closed loop system. The problem is called "almost disturbance decoupling with measurement feedback". The problem is solved in terms of "almost (A, B)-invariant subspaces", which is a high gain feedback generalization of the usual (A, B)-invariant subspaces. Therefore the almost (A, B)-invariant subspaces are, in some sense, related to the zeros at infinity as the (A, B)-invariant subspaces are related to the finite zeros. The theory is presented in [1].

The same almost invariant subspaces are useful for solving the "singular quadratic optimal control problem" as presented by Silverman. A singular quadratic performance index should be minimized via state feedback plus dirac distribution inputs. The basic idea is that the distribution inputs should instantaneously move the initial state to a more favourable one without showing up in the performance index. The distribution space is determined via Silvermans´s structure algorithm see e.g. [2]. This algorithm essentially computes the structure of the zeros at infinity.

The zero structure at infinity, also called the latency kernel, was also discussed by Heymann in connection with feedback realization and causal factorization problems, see [3].

Finally it should be noted that the "interactor", defined by Falb and Wolovich [4], is a polynomical matrix, which describes the zero structure at infinity. It is only defined for left or right invertible systems. A more generally valid description of the zero structure at infinity is found in my own "structure matrix" (calculated for an ustable region consisting of the infinity point only). For right invertible systems the interactor and the left structure matrix are each others inverses at infinite frequencies.

References

[1] J C Willems: Almost invariant subspaces: An approach to high gain feedback design, Part I, *IEEE-AC*, AC - 26, 235 - 252, Febr 1981 and Part II, submitted to IEEE-AC.

[2] L M Silverman: Discrete Riccati equations: alternative algorithms and system theory interpretations, *Control and dynamic systems* vol. 12, 313 - 385, Academic Press, New York 1976.

[3] J Hammer, M Heymann: Causal factorizations and linear feedback. *Siam J. Control and Optimization* 19, 445 -468, 1981.

[4] W A Wolovich, P L Falb: Invariants and canonical forms under dynamical compensation. *Siam J.* Control and Optimization, 14, p 996, 1976.

2.2 Root loci

The infinite zero structure of the system also plays an important role in the study of root loci. Some of the branches tend to the infinite zeros when the feedback gain tends to infinity.

Owens considers the linear quadratic optimal control problem with scalar weighting k^{-1} on the input. The closed loop poles, that tend to infinity (to the infinite zeros), as k tends to infinity are studied. The orders, multiplicities and asymptatic directions are examined. Here the order of an infinite zero is n if the closed loop pole goes to infinity as k^n. For more details see [1].

It is well known that the closed loop poles tend to the zeros of the loop transfer matrix as the feedback gain tends to infinity. These zeros can, however, be placed, to some degree, by choice of the feedback matrix. Stevens studies this zero placement problem from a geometric point of view. The analysis is based on result by Byrnes, who also talked about these problems, see [2].

Trentelman considers, not only the eigenvalues of the closed loop system, but also the eigenvectors as the feedback gain tends to infinity. These eigenvector are characterized in terms of the almost (A, B)-invariant subspaces, see ref [1] of section 2.1.

References

[1] D H Owens: On the computation of optimal system asymptotic root loci. IEEE-AC-25, 100 - 102, 1980.

[2] R W Brockett, C J Byrnes: Multivariable Nyquist criteria, root loci and pole placement: A geometric viewpoint. IEEE-AC-26, 271 - 283, 1981.

2.3 Systems over rings

A state space system, where the entries of the A, B and C matrices belong to a ring, is called a system over a ring. For example, a certain class of difference - differential systems can be described in this way. The ring is then taken to be polynomials in the delay operator.

Hautus talked about generalization of (A, B) - invariant subspaces, also called controlled invariant subspaces, to systems over rings. In this case a subspace V satisfying $A V \subset V + \text{im} B$ is called a controlled invariant subspace C.I.S., while V is a controlled invariant subspace of feedback type C.I.S.F, if there exists an F such that $(A + BF) V \subset V$. It is easy to show that a C.I.S.F. is always also a C.I.S. The converse is not true. The largest C.I.S. in $\ker C$ called V^* can be shown to exist. Hautus examined the question when V^* is also a C.I.S.F. For a survey paper of systems over rings see [1].

Schumacher considers continuous time systems over the ring of polynomials in the delay operator. He has a method to stabilize finitely many poles with controllers over the field of reals (i.e. the controller is an ordinary, continuous time, finite dimentional system). The results are presented in his upcoming thesis [2].

References

[1] E D Sontag: Linear systems over commutative rings: A survey. Richerche di Automatica, 7 : 1 - 34, 1976.

[2] J M Schumacher: Dynamic feedback in finite and infinite dimensional systems, 1981.
(Math. Dept., Vrije Universiteit, Amsterdam).

2.4 Polynomial algebra

A few words should also be said about Fuhrmann´s polynomial approach. His starting point is a system described in polynomial matrix form. He then constructs a state space consisting of polynomial vectors. The state space mappings A, B and C are constructed via shifts and projections on the polynomial vectors. The ideas probably come from Kahman´s module theory. The theory is fairly abstract and very elegant. The basic results are presented in [1] and some recent results in [2]. In his talk Fuhrmann used his theory to develope some algebraic stability criteria. The results will be published later.

Fuhrmann´s approach has been used by many others. One example is Wimmer, who talked about characterizations of polynomial matrices.

References

[1] P A Fuhrmann: Algebraic system theory: An analyst´s point of view. J Franklin Inst. 301, 521 - 540, 1976.

[2] P A Fuhrmann: Duality in polynomial models with some applications to geometric control theory. IEEE - AC -26, 284 - 295, 1981.

2.5 Robust control

Ackermann considers the problem of finding controllers for a fighter aircraft. He uses a gain scheduling technique and designs controllers for four different flight conditions. Each controller should sufficiently damp the poles at the flight conditions for which it is designed. Furthermore, the configuration should be robust in the sense that each controller should stabilize the other flight conditions. It was pointed out to the speaker that the problem of simultaneous stabilization has recently been solved by Vidyasagar [1]. Ackermann´s work is presented in [2].

A different robustness problem was presented by Jacques Willems. He considers a linear state space system with an additional term which is nonlinear in the state. The nonlinearity should satisfy a conicity condition. A linear state feedback should be found, such that the closed loop system is stable for all nonlinearities of admissible type. The problem is closely related to a stockastic stabilizability problem, see [3].

References

[1] M Vidyasagar, N Viswanadham: Algebraic design techniques for reliable stabilization. Submitted to IEEE - AC, 1981.

[2] J Ackermann: Parameter space design of robust control systems. IEEE - AC - 25, 1058 - 1072, 1980.

[3] J L Willems, J C Willems: Robust stabilization of uncertain systems. Submitted to Siam Journal on Control and Optimization, 1981.

2.6 The Bremen group session

During one late night session the organizers of the linear part of the workshop, the Bremen group, presented its work. The group was formed in 1976 at the university of Bremen and consists of both mathematitians and engineers.

Linnemann talked about the problem of decoupling structured systems. A structured system is a system in state space form where some of the entries of A, B and C are known to be equal to zero. The admissible controllers are constant state feedback plus constant feed forward from the command input. A system can be decoupled if the transfer function from the command input to the output can be made diagonal. The problem considered is to find conditions for when a structured system generically can be decoupled. The work is based on some decouplability results in [1].

Prätzel - Wolters presented a canonical form for an uncontrollable pair (A, B). The canonical form resembles Luenberger´s canonical form for controllable pairs.

A subspace V is (C, A) - invariant if there exists a K such that $(A + KC)V \subset V$. Hinrichsen and Münzner presented a parametrization of the (C, A) invariant subspaces of an observable pair (C, A).

The results are not published yet, but other results by the group can be found in [2] and [3].

References

[1] P L Falb and W A Wolovich: Decoupling in the design and synthesis of multivariable control systems. IEEE - AC - 12, 201 - 208, 1967.

[2] D Prätzel - Wolters: Brunovsky equivalence of system matrices: The reachable case. IEEE - AC - 26, 429 - 434, 1981.

[3] H F Münzner, D Prätzel - Wolters: Minimal bases of polynomial modules, structural indices and Brunovsky - transformations. Int, J Contr. vol 30, 291 - 318, 1979.

2.7 Algorithms

It was pointed out by many of the participants that it is extremely important to find numerically good algorithms for system theory problems. An equally important task is to present these algorithms in form of portable software. The step from a numerical algorithm to a well behaving computer program is long and toilsome.

Laub presented a technique for computation of the solution to a Riccati differential (or difference) equation. In [1] a Schur method for solving the algebraic Riccati equation is given. This was generalized to the differential equation. The computations involved are a Schur decomposition of the Hamiltonian, matrix exponentiation of triangular matrices with eigenvalues in the left half plane and a time integral of matrix exponentials. An algorithm for the Schur decomposition can be found in [1]. The particular matrix exponentials can be computed with the recursive formulas [2] and the time integral can be computed with the algorithm in [3].

Eising presented an algorithm for the following problem. Given a polynomial matrix P with linearly independent rows and no zeros. Find a polynomial matrix Q, such that $U \triangleq \begin{bmatrix} P \\ Q \end{bmatrix}$ becomes unimodular. Such an algorithm would be very useful, particularly if it also gives the inverse of U. The problem is reformulated as a problem in the state space framework. The algorithm seems to me to be very similar (maybe identical) to the one in [4]. The drawback of the algorithm is that it involves a transformation to Luenberger canonical form. A related algorithm for GCD extraction can be found in [5].

References

[1] A J Laub: A Schur method for solving algebraic Riccati equations. IEEE - AC - 24, 913 - 921, 1979.

[2] B Parlett: A recurrence among the elements of functions of triangular matrices. Linear algebra and applications 14, 117 - 121, 1976.

[3] C van Loan: Computing integrals involving the matrix exponential. IEEE - AC - 23, 395 - 404, 1978.

[4] A Kontos, J B Pearson: Computation of a unimodular matrix. Technical report 7916, dec 1979, Rice University, Houston, Texas.

[5] L M Silverman, P van Dooren: A system theoretic approach for GCD extraction. Proc CDC, San Diego, Jan 1979.

2.8 Sociological aspects

Rosenbrock pointed out that the next twenty years will no doubt provide us with a very rapid technical development, comparable to the one in Great Britain in the early nineteenth century. Then machines replaced some of the human muscle power. Now machines will replace some of the human mental power. When a rapid development takes place we have many opportunities for making choices. We should take care of these opportunities and influence the development.

Rosenbrock points to many historical analogues and the main message of his talk is the following. We should make the choices so that the machines (computers and the like) develope into tools for humans. The human (computer operator) should feel that he is in full control of the machine and able to use it to enhance the effects of his skills. The machine should not develope into a device which replaces human skills and requires humans only for servicing it.

3. Schedule of speakers and subjects

MONDAY, JUNE 22, 1981

Morning Session

9.00	J. C. Willems: (Groningen)	Almost Disturbance Rejection by Measurement Feedback
10.00		
		BREAK
10.15	C. I. Byrnes: (Cambridge, MA)	Root Loci in one and in several variables, with applications to problems of output feedback
11.15		
		BREAK
11.30	J. M. Dion (Grenoble)	Infinite Zeros, Application to Model Following Control
12.30		

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Afternoon Session

14.30	J. L. Willems: (Gent)	Criteria for Stabilization of Stochastic Systems and for Robust Stabilization of Deterministic Systems
15.00	C. Conte (Genova) A. Perdon (Padova) :	Generalized state space realizations of non proper rational transfer functions
15.30		
		BREAK
15.45	D. H. Owens: (Sheffield)	On the orders of optimal system infinite zeros
16.15	A.J.J. van der Weiden: (Delft)	On decoupling zeros at infinity
16.45		
		BREAK
17.00	O. H. Bosgra: (Delft)	On Invariants and the partial realization problem for linear multivariable systems
17.30	M. Köhne: (Siegen)	Synthesis and Simulation of State Observers for Polynomic Systems in Population Dynamics
18,00		

TUESDAY, JUNE 23, 1981

Morning Session

9.00	P. A. Fuhrmann: (Beer Sheva)	On the application of polynomial models to some classical stability criteria
10.00		
		BREAK
10.15	M. Heymann: (Haifa)	System factorization: feedback and stability
11.15		
		BREAK
11.30	M. L. J. Hautus: (Eindhoven)	Decoupling of systems over rings
12.30		

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Afternoon Session

14.30	W. A. Coppel: (Canberra)	Polynomial lattices
	H. Wimmer: (Würzburg)	Polynomial matrices and dualities
15.30		
		BREAK
15.45	R. Eising: (Eindhoven)	Polynomial matrices and feedback
16.15	L. Pernebo: (Lund)	Algebraic Design Theory for Linear Multivariable Systems
16.45		

WEDNESDAY, JUNE 24, 1981

Morning Session

9.00	A. G. Laub: (Los Angeles)	Schur Techniques for Riccati Differential Equations
10.00		BREAK
10.15	J. Ackermann: (Oberpfaffenhofen)	Robust Flight Control System Design
	D. Kaesbauer: (Oberpfaffenhofen)	D-Decomposition in the Space of Feedback gains for arbitrary Pole Regions
11.15		BREAK
11.30	H. H. Rosenbrock: (Manchester)	Automation and Society
12.30		

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14.00	Sondergeld:	Stability criteria
	P.K. Stevens: (Cambridge, Mass)	Zeros of linear multivariable systems, zero placement and the root-loci
15.00		

EXCURSION

20.30	A. Linnemann: (Bremen)	Decoupling of structured systems
	D. Prätzel-Wolters: (Bremen)	Canonical forms for uncontrollable systems
	D. Hinrichsen: H.F. Münzner: (Bremen)	Parametrization of (C,A)-invariant subspaces
23.00		

THURSDAY, JUNE 25, 1981

Morning Session

9.00	M. Silverman: (Los Angeles)	Spectral Theory of the Linear Quadratic Control Problem for Continuous Time Systems
10.00		BREAK
10.15	A. S. Morse: (New Haven)	Generic poleplacement by constant output feedback
11.15		BREAK
11.30	S. Mitter: (Cambridge, MA)	Lax-Phillips Scattering Theory and Systems Theory
12.30		

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Afternoon Session

14.30	A. C. Antoulas: (Zürich)	The Minimality Problem of Generalized Invariant Subspaces with Applications to Linear Systems
	A. Yannakoudadis: (Grenoble)	Output Feedback Equivalence for Linear Multivariable Control Systems
15.30		BREAK
15.45	N. Karcanias: (London)	The Homogeneous Matrix Pencil $sF-\hat{s}G$: Equivalence, Smith forms and Minimal Basis Considerations
16.15	A.I.G. Vardulakis: (Cambridge)	On certain connections between: Infinite Zeros of proper rational Matrices, Dynamic Equivalence and the "Interactor"
16.45		
17.00	Z. Bartosiewicz: (Bialostocka)	Completability of neutral systems
17.30	H.L. Trentelman: (Groningen)	Multivariable root loci, high gain feedback and (almost) controlled invariant subspaces
18.00	M.K. Solak: (Warszawa)	A differential representation for multivariable linear systems with disturbances
18.30		

FRIDAY, JUNE 26, 1981

Morning Session

8.15

A. Olbrot: (Warszawa)	Finite-time control of linear systems over rings
K. M. Przyluski: (Warszawa)	Linear Discrete-Time Systems with Infinite Number of Delays in State and Control Systems Defined over a Bezout Domain

B R E A K

L. Pandolfi (Torino)	On the Zeros of Transfer Function of Delayed Systems
J. M. Schumacher: (Amsterdam)	Stabilizing a Delay System by Integral Control

10.15