MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 11/1992

Regelungstheorie

15. 3. bis 21. 3. 1992

Die Tagung fand unter Leitung von H. W. Knobloch (Würzburg) und M. Thoma (Hannover) statt. Ein Hauptthema der Tagung war die in den letzten Jahren sehr in den Vordergrund getretene Theorie der Steuerung und Regelung nicht-linearer Systeme, der fast ein Drittel aller Vorträge gewidmet waren. Es ist geplant, daß sich auch die nächste Tagung über Regelungstheorie mit mathematischen Methoden der nicht-linearen Steuerungstheorie und besonders mit deren effizienter Implementierung beschäftigen wird. In den 80er Jahren wurden die theoretischen Grundlagen für eine Verallgemeinerung auf nicht-lineare Systeme vieler in den Ingenieurwissenschaften für lineare Systeme üblichen Designverfahren und Entwicklungsmethoden gelegt. A. Krener präsentierte numerische Verfahren, die wichtige Problemstellungen, wie etwa Linearisierung durch Wahl geeigneter nicht-linearer Steuerungsfunktionen oder Optimale Steuerung, im Sinne einer "nonlinear systems toolbox" für kubische Systeme effizient berechnen. H^∞-optimale Steuerung war das Thema von H. Kwakernaak, der eine auf der J-spektralen Faktorisierung basierende Berechnungsmethode vorstellte. A. Isidori gab eine Lösung der Störungsunterdrückung durch Ausgangsrückführung an, die frühere Resultate von A. van der Schaft verallgemeinert. A. Halanay sprach über das Problem der Störungsunterdrückung bei zeitabhängigen linearen Systemen. Die mehr technischen Aspekte der H^∞-Optimierung kamen in den Vorträgen von S. Engell über Störungsunterdrückung und von Q. H. Wu über dezentralisierte Steuerung zum Ausdruck. Mit mehr mathematischen Fragen beschäftigte sich der Vortrag von D. Flockerzi über die Konstruktion von Beobachtern durch Fehlerrückführung unter Dichotomie-Voraussetzungen anhand invarianter Mannigfaltigkeiten. S. Nikitin gab sowohl neue auf Indextheorie begründete Bedingungen für die Stabilisierung eines nicht-linearen Systems durch eine glatte Feedback-Steuerung als auch hinreichende Bedingungen für die Stabilisierung durch stückweise glatte FeedbackSteuerungen auf kompakten Mengen an.

Fragen der optimalen Steuerung nicht-linearer Systeme standen im Mittelpunkt der Vorträge von F. Kirillova und R. Gabasov, die sich mit konstruktiven Aspekten der Steuerung bzw. Zustandsberechnung beschäftigten. Der Übergang von notwendigen zu hinreichenden Bedingungen, d. h. die Synthese einer optimalen Feedback- oder Closed-Loop-Steuerung aus extremalen Open-Loop-Steuerungen unter Verwendung notwendiger Bedingungen höherer Ordnung stand im Mittelpunkt der Vorträge von H. Sussmann und H. Schättler. Ein numerischer Algorithmus zur Berechnung optimaler Feedback-Steuerungen wurde von T. Birkhölzer vorgetragen. A. Sarychev präsentierte hinreichende Bedingungen für die lokale Optimalität von bang-bang-Steuerungen.

R. V. Gamkrelidze präsentierte einen Satz, demzufolge Vektorfelder in endlich erzeugten Moduln, die unter inneren Derivationen invariant sind, auch invariante innere Automorphismen des Flusses erzeugen. Dies erlaubt, Distributionen mit Singularitäten zu liften und führt zu einer äqui-varianten Verallgemeinerung des

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Orbit-Satzes. F. Albertini untersuchte die Orbits zeitdiskreter analytischer Systeme, insbesondere die Fragen der Äquivalenz von Transitivität und "forward accessibility". Die globale Analysis nicht-linearer Systeme war das Thema des Vortrages von F. Colonius, der die neuen Konzepte der Kontrollmenge und des Kontrollflusses vorstellte.

Ein sehr interessanter, wenn auch kontroverser Vortrag wurde von J. Willems gegeben, der eine neue Auffassung von System und Feedback-Steuerung vorschlug, die ohne die Unterscheidung von Eingangs- und Ausgangsgrößen operieren solle. Dem wurde von J. Lückel in seinem Vortrag über die Darstellung physikalischer Systeme im Rechner heftig widersprochen, und der Konsensus der anwesenden Ingenieure war wohl doch, daß die Problemstellung bis auf wenige Ausnahmefälle eine genaue Festlegung von Ein- und Ausgangsgrößen vorschreibe. J. Ackermann besprach theoretische Grundlagen zur Feedback-Steuerung von allrad-gelenkten Fahrzeugen. A. Munack diskutierte den Entwurf von Experimenten mit dem Ziel, bezüglich mehrerer Modell-Alternativen zu unterscheiden. J. Lunze sprach über die Modellierung unter der ausschließlichen Zuhilfenahme qualitativer Aspekte, und H. A. Nour-Eldin diskutierte strategische Punkte von Lösungen von Riccati-Differentialgleichungen.

F. Lamnabhi-Lagarrigue gab eine Charakterisierung des Eingangs-Ausgangsverhaltens Hamiltonscher Systeme. Mit der Frage der Eingangs-Ausgangslinearisierung nichtlinearer Systeme beschäftigte sich auch F. Allgöwer, der an mehreren Beispielen aufzeigte, daß Linearisierung per se nicht etwas bona fide Gutes sein muß, sondern daß Nichtlinearitäten sich durchaus positiv zur Stabilisierung verwenden lassen. Die Frage, inwieweit es möglich sei, ein Maß dafür anzugeben, wie weit ein nichtlineares System von einem linearen System entfernt sei, war, wie auch in F. Allgöwers Vortrag, das zentrale Thema von M. Fliess, der dazu den Begriff des Defekts, dem differential-algebraische Graduntersuchungen zugrundeliegen, als Maß vorschlug.

E. Sontag präsentierte Resultate über mehrere Typen nicht-linearer Systeme, die durch Saturationsvorgänge aus linearen Systemen entstehen und ihren Ursprung in der Theorie der Neuronalen Netze haben. Die Möglichkeit, Systemtheorie als Ansatzpunkt zur Integration von Analog- und Digitalrechnern zu sehen, wurde diskutiert. Die Modellierung synchronisierter Flußsysteme mittels linearer Differenzengleichungen unter Verwendung der (max,+) Algebra wurde von G. Olsder dargelegt. D. Franke präsentierte einen gemeinsamen Zugang zu zeit-diskreten linearen Systemen und endlichen Automaten, in dem Boole-sche durch arithmetische Operationen ersetzt werden. Fragen der Robustheit linearer Systeme waren das Thema des Vortrages von D. Hinrichsen über das Spektrum von Matrizen unter Störungen mit beschränkten Matrizen. A. Bartlett gab Beispiele, die aufzeigen, daß die Kharitonov-Extrempunkte im allgemeinen nicht für eine Analyse der Sprungantwort ausreichen.

Mehrere Teilnehmer hielten Vorträge zum Thema "Differential Inclusions". A. Kurzhanski präsentierte Resultate einer Theorie singulärer Störungen, A. G. Butkowski besprach Elemente eines Phasenportraits und V. I. Blagodatskikh besprach Variationen in diesem Zusammenhang. E. F. Mischenko beendete die Konferenz auf amüsante Weise mit einer Anekdote über L. S. Pontryagin und Kolmogoroff.

Heinz Schättler, Washington University, St. Louis

Vortragsauszüge

J. ACKERMANN :

Feedback Structures for Robust Four-Wheel Steering of Cars

Recently several car manufacturers have introduced four-wheel steering. Such systems are analyzed from a control theoretic point of view and two results are presented: i) an integrating unit feedback of the measured yaw rate to front wheel steering decouples two modes, that is the lateral motion of the front axle (to be controlled by the driver, he only has to keep a mass point on his planned path) and the yaw motion. A result of the above control law is that the yaw eigenvalues get a speed-independent natural frequency. ii) a velocity-scheduled feedback of the yaw rate to rear-wheel steering preserves the speed-independent yaw frequency and makes also yaw damping independent of speed. Some robust control problems for the nonlinear car model are formulated.

F. ALBERTINI :

Transitivity and Accessibility of Discrete-Time Analytic Systems

We discuss the following question for discrete-time nonlinear systems: when does accessibility follow from transitivity of a natural group action, in analogy with the classical continuous-time "positive form of Chow's lemma". We present some results that establish the desired implication for analytic systems in several cases: (1) compact state space, (2) under a Poisson stability condition, (3) in a generic sense. In addition we also establish that if a nonlinear system is forward accessible, then generically it is possible to reach an open set in a number of steps that is equal to the dimension of the state space.

F. ALLGÖWER :

On Input/Output Linearization of Nonlinear Systems

Input/Output linearization has attracted a lot of attention during the past years. Its idea is to use nonlinear change of coordinates and nonlinear feedback in order to render the I/O behaviour of a nonlinear system linear. The so linearized system can then be controlled with a linear controller to satisfy desired performance specifications. The advantage of this control scheme is that the linearization step is independent from the design for performance. Necessary iterations can be dealt with completely on a linear level.
As can be illustrated with some simple examples, linearity of the I/O behaviour is not desirable for all control problems. And even when linearization techniques can be applied it is, from an engineering point of view, not necessary to achieve **exact** linear behaviour. The definition of measures for the size of nonlinearity in the I/O channel facilitates the use of approximation techniques. Such definitions are given and it is shown how those measures can be used in connection with numerical parameter optimization to find "almost-linearizing" feedback laws.

A. BARTLETT :

Vertices and Segments of Interval Plants Are Not Sufficient for Step Response Analyses

Interval plants are of interest in control theory as models of uncertain systems. They are useful because many worst-case analyses of these models are simple to carry out. For example, robust stability of an interval plant can be determined by investigating only the four Kharitonov vertices of the denominator polynomial. Also, the maximum peak of the Bode magnitude plot can be found using just 16 plant vertices. These 16 vertices are connected by 32 special line segments. Most stability and frequency domain analyses that cannot be done using only the special vertices can be carried out using just the segments. From these results, it is tempting to conjecture that the 16 vertices or at best the 32 segments are adequate for step response analyses. This paper presents examples showing that these conjectures are not true.

Th. BIRKHÖLZER :

Numerical Nonlinear Regulator Design

For discrete-time systems $x_{t+1} = f(x_t,u_t)$ where f is continuous, we consider the state regulation problem from a prespecified region of initial conditions G.

It is shown that if this problem has a solution, then minimizing a cost functional with terminal cost and free terminal time results in a practical control Lyapunov funcion, and an associated piecewise constant controller k(x) exists such that the controlled system $x_{t+1} = f(x_t,k(x_t))$ is practically asymptotically stable (p. a. s.) from G to a neighbourhood of the origin $B(r_0)$, $r_0 > 0$.

The main result then is a finite computer implementable algorithm and the demonstration that it defines (and thus enables computation of) a p. a. s. controller from G to $B(r_0)$, if one exists.

A. G. BUTKOVSKI :

The Geometrical Approach to the Control Systems with Lumped (CDS) and Distributed Parameters (DPS) Based on Concept of the Phase (State)-Space Portraits of the Differential Inclusions

It is outlined the concept of the Phase(State)-Space Portraits (PSP) for differential inclusions (DI) on M^n. The series of the examples on R^2 and S^2 and other manifolds are given. It is presented decomposing reducing method for PSP DI by means of the apparatus of the fibre bundle. It is considered correspondence between CDS and DPS like continouos media and it is derived a formula for Laplace operator (Ref: A. G. Butkovski , "Phase Portraits of Control Dynamical Systems", Kluwer Academic Publishers, 1991, book)

V. BLAGODATSKIKH : See p. 13

F. COLONIUS :

Global Analysis of Nonlinear Control Systems

For every control affine system one can associate a dynamical system, the 'control flow' on the product of the set U of admissible control functions and the state space M. This is, with the shift and an appropriate topology on U, a continuous skew product flow. Properties of the control flow turn out to be equivalent to control theoretic properties (e.g. topological transitivity corresponds to controllability). Furthermore, concepts from Conley's view of dynamical systems (chain recurrence) combined with ideas from geometric control allow the proof of controllability for nonlinear systems, e.g the controlled Lorenz equation.

S. ENGELL :

H^∞-Optimization Including Specifications of the Transient Response

Realistic design problems are characterized by at least 3 types of specifications:

- hard constraints due to model uncertainty and actuator limitations
- desired disturbance rejection, esp. at low frequencies
- desired transient behaviour, characterized e. g. by maximal overshoot or settling time.

It is discussed how these specifications can be mapped into constraints on the frequency response over different frequency intervals. These constraints are approximated such that at each frequency, the closed-loop frequency response lies in a disc in the complex plant, and the center points and radii are rational functions of ω. The existence of a stabilizing controller which meets these specifications can then be tested analytically.

M. FLIESS :

Flatness and Defect of Nonlinear Systems

A nonlinear dynamics can be dynamically feedback linearized if there exists an output such that:
1) The input-output system is right-invertible.
2) The control and the state variables can be expressed as functions of the output variables an of a finite number of their derivatives.

This property, which in fact is independent of any distinction between the variables, can be given an algebraic characterization in the language of differential fields. The flat systems, which are so defined, are indeed very common, as demonstrated by several mechanical examples. They also can be understood as another nonlinear extension of controllable linear systems. The departure from flatness is measured by an integer called the defect and which in some sense is related to an inherent vibrating structure within the system. An example is exhibited and it is shown how to use oscillatory controls in order to achieve a desired behaviour.

D. FLOCKERZI :

Invariant Manifolds in Nonlinear Control Theory

We consider a smooth affine control system

$$\dot{x} = f(x,w) + g(x,w)u \ , \quad \dot{w} = s(w) \ , \qquad y = h(x,w) \tag{1}$$

and suppose that the state feedback regulator problem can be solved by means of

$$u = u(x,w) \tag{2}$$

in a nonlocal way so that initial values (x_0,w_0) from a "big" initial set Ω_0 lead to solutions (x(t),w(t)) of the closed loop (1&2) that zero the output y asymptotically. It is our goal to achieve the same (nonlocal) result with dynamic output regulation. To this end we construct a nonlinear observer with internal state $(\hat{x},\hat{w})$ and feedback law $u = u(\hat{x},\hat{w})$. The gain matrix $K(t,\hat{x},\hat{w})$ is to be designed such that the interconnection of the plant and the observer possesses an exponential dichotomy on the limit sets of the state feedback regulator system (1&2). The main tool in the existence proof is coming from the (nonlocal) theory of integral manifolds ("asymptotic phase").

D. FRANKE

Discrete Event Systems and Discrete Time Systems in a Unifying View

The theory of finite automata offers an access to modelling, analysis and synthesis of discrete event systems. The state equations of finite automata are usually defined over a Galois field rather than the field of real or complex numbers. It is shown, however, that finite automata can closely be related to classical discrete time systems. To this end a novel representation of Boolean functions is introduced which uses arithmetical operations on Boolean variables. This allows imbedding finite state machines into the class of discrete time systems. There is an appealing class of incompletely specified automata which can be modelled by linear difference equations. The dynamical behaviour of these systems is studied via eigenvalue analysis. Prescribed periodic sequences can be achieved by logical controller design, based on eigenvalue assignment.

R. F. GABASOV :

Estimation Problem and Synthesis of Estimators in the Optimal Control Theory

Estimation of states of dynamic systems is of great importance in control problems under conditions of uncertainty. Up to now this problem is mainly elaborated in stochastic variants. Recently nonstochastic models began to appear. In this paper a new approach to solve the problem of estimation for dynamic systems under uncertainties is suggested. An algorithm of operating optimal estimators for the solution of the problem of position estimation in real time mode is justified. The results are applied to construct optimal output feedback.

R. V. GAMKRELIDZE :

Existence of Flows in Modules

A general existence theorem of flows in $C^{\infty}(M)$-modules and its several applications were discussed. For a tangent bundle it could be formulated in the following way: Suppose M is a smooth manifold, Vect M is the $C^{\infty}(M)$-module of all smooth vector fields on M, F is an arbitrary finitely generated submodule in Vect M. Then the following implication holds for $X \in$ Vect M:

$$\operatorname{ad} X\, F \subset F \;\Rightarrow\; \operatorname{Ad} e^{tX}\, F \subset F .$$

A. HALANAY :

Stabilizing Compensators with Disturbance Attenuation for Linear Time-Varying Systems

Report of recent results obtained in Bucharest concerning necessary and sufficient conditions for existence of a stabilizing compensator with disturbance attenuation in the case of linear systems with time-varying coefficients, both in continuous-time and discrete-time situations. Some of the results are stated with respect to general evolutionary processes. The case of white noise perturbations is also considered. In the context, a time-varying Nehari-type result and robustness aspects are discussed.

D. HINRICHSEN :

On Spectral Variations under Bounded Real Matrix Perturbations

Consider the set of eigenvalues of a perturbed matrix $A + \Delta \in \mathbb{R}^{n\times n}$ where A is given and $\Delta \in \mathbb{R}^{n\times n}$, $\|\Delta\| < \rho$ is arbitrary. We determine a lower bound for this spectral value set which is exact for normal matrices A with well separated eigenvalues. We also investigate the behaviour of the spectral value set under similarity transformations. The results are then applied to stability radii which measure the distance of a matrix A from the set of matrices having at least one eigenvalue in a given closed instability domain $\mathbb{C}_b \subset \mathbb{C}$.

A. ISIDORI :

Disturbance Attenuation for Nonlinear Systems

A solution to the problem of disturbance attenuation via measurement feedback, with internal stability, for an affine nonlinear system is described. The proposed approach is based on the solution of two Hamilton-Jacobi-Isaacs equations, one associated with the design of a state-feedback law and one associated with the design of an output-injection law. The approach does not involve specific assumptions on the linear approximation of the controlled plant at an equilibrium point, and therefore allows nonhyperbolic equilibria for the associated Hamiltonian vector fields.

F. M. KIRILLOVA :

Construction of Optimal Regulators for Linear Control Systems

Three types of regulators (controllers) to solve the synthesis problem for the dynamic system

$$\dot{x} = Ax + bu , \; x(0) = x_0 , \; t \in T = [0,t^*] , \; |u(t)| \leq 1 , \; Hx(t^*) = g$$
$$c'x(t^*) \to \min!$$

are investigated. These regulators can generate bang-bang controls, piecewise constant and piecewise continuous controls. Critical analysis of classical statements is made, flexible feedback is introduced and algorithms of operating controllers are described.

A. J. KRENER :

The Design of Nonlinear Controllers and Observers

We present several methods for the design of controllers and observers for nonlinear systems with quadratic and cubic nonlinearities. These methods are perturbation of linear design techniques. From the linear part of the plant, one does a linear design and then one adds sequentially quadratic and cubic terms to the controller or observer to achieve improved performance over a wide range of operating conditions.
The basic mathematical techniques are two. The first is linearization by change of coordinates, feedback and input/output injection. The second is optimi zation, in particular, the term by term solution of the Hamilton-Jacobi-Bellman equation.

These methods have been incorporated into a MATLAB based toolbox called the NONLINEAR_SYSTEM_TOOLBOX. During the course of the lecture, three programs are demonstrated for the feedback linearization (pc3), optimal stabilization (hjb3) and optimal regulator (sewo3). Using SIMULAB we simulate these designs and exhibit the improved performance that is possible by adding quadratic and cubic terms to linear designs.

A. KURZHANSKI :

Singular Perturbation Theory for Differential Inclusions and Uncertain Systems

A direct propagation of singular perturbation theory for ordinary differential equations does not hold in the case of differential inclusions. Here we suggest a nonstationary matrix-valued perturbation technique which allows to separate trajectory tubes of differential inclusions and give a basic solution to the perturbation problem for differential inclusions. The results are then applied to problems of viability theory and those of guaranteed estimation of the states of linear dynamic systems under observations with unknown but bounded errors of irregular nature.

H. KWAKERNAAK :

Solution of H_∞ optimal control problems by J-spectral factorizations

By a frequency domain approach to the "standard" linear time-invariant H_∞ optimal regulator problem it may be shown straightforwardly that all "suboptimal" solutions may be obtained by J-spectral factorization. For finite-dimensional systems this factorization is rational and may be reduced to two polynomial matrix factorizations - one for the denominator, one for the numerator. One of the several algorithms that are available for polynomial J-spectral factorization relies on the solution of an algebraic Riccati equation. At the optimal solution of the H_∞-problem (as opposed to suboptimal) this algebraic Riccati equation fails to have a solution because the J-spectral factorization is no longer canonical. Analysis of the algebraic Riccati equation leads to a numerically feasible method for the computation of all optimal solutions.

F. LAMNABHI-LAGARRIGUE

Adjoint and Hamiltonian Input-Output Differential Equations

Based on recent developments in the theory of variational and Hamiltonian control systems by Crouch and Van der Schaft, this paper answers two questions: given an input-output differential equation description of a nonlinear system, what is the adjoint variational system in input-output differential form and what are the conditions for the system to be Hamiltonian, i. e. such that the variational and the adjoint variational systems coincide? This resulting set of conditions is then used to generalize classical conditions such as the well-known Helmholtz conditions for the inverse problem in classical mechanics.

J. LÜCKEL

Mapping Physical and Technical Systems on a Computer

Before designing and realizing control systems one has to solve the problem of modelling. In the field of mechatronics additionally one has the problem of complexity: The systems are big (> 50, 100 DOF) and are composed of many subsystems of different physical basic principles (mechanical, electrical, hydraulic,...) and their different mathematical descriptions. In order to get some organization principle it is proposed to describe mechanical systems in three more or less equivalent representations: a) physical repr., b) a block oriented repr., c) a data repr. For the block oriented repr. a dynamic system language syntax is defined and a compiler/interpreter is realized which allows numerical treatment of complex mechatronic systems.

J. LUNZE :

Qualitative Modelling of Dynamical Systems

Consider a discrete-time continuous-variable system for which only a quantised state measurement [x(k)] is available. The problem is to set up a qualitative model that for a given quantised initial state [x(0)] and quantised input sequence [u(k)] (k = 0,1, ...) describes the sequence of quantised states [x(k)]. First, it can be shown that the relation between [x(0)] and [u(k)] and [x(k)] (k = 0,1, ...) is ambiguous. Hence, the qualitative model is nondeterministic. Second, necessary and sufficient conditions are derived under which nondeterministic or stochastic automata represent qualitative models of a linear system. Finally, it can be shown that every such model provides spurious trajectories, i. e. trajectories that no physical system can perform, because the automaton possesses a Markov property.

E. F. MISCHENKO :

On a Problem for Parabolic Equations Connected with Optimal Pursuit

Let there be in n-dimensional space two moving points, one of which is controlled according to the law $\dot{z} = f(z,u)$ and the other is a random point of the Markov type with transition density $p(\sigma,x,\tau,y)$ satisfying the Kolmogorov equation

$$\frac{\partial p}{\partial \sigma} + a^{ij}(\sigma,x)\frac{\partial^2 p}{\partial x^i \partial x^j} + b^i(\sigma,x)\frac{\partial p}{\partial x^i} = 0 \qquad (1)$$

Suppose that moving together with $z(t)$ is a small neighborhood $\Gamma_{z(t)}$ of $z(t)$, for example a neighborhood bounded by a sphere $\Sigma_{z(t)}$ centered at the point $z(t)$ and of radius ε.
It is required to calculate the probability of the following event: that in the time interval $\sigma \leqq t \leqq \tau$ the random point will be covered by $\Gamma_{z(t)}$, that is, the random point crosses the surface $\Sigma_{z(t)}$. Denote this probability by $\psi(\sigma,x,\tau)$.
In our talk we are considering the formula for this probability which has been received by A. N. Kolmogorov

$$\psi(\sigma,x,\tau) = \varepsilon^{n-2}\int_{\sigma}^{\tau} p(\sigma,x,s,z(s))\beta(s)\, ds + O(\varepsilon^{n-1}) \qquad (2)$$

A. MUNACK :

Design of Experiments for Discrimination between Model Alternatives

In identification of dynamic models for biotechnical processes one is sometimes confronted with the situation that models with different structures may be fitted equally well to the measured experimental data. Some possibilities for design of a further experiment in order to detect the most suitable model structure were presented and applied to different growth models for the pellet-forming basidiomycete Cyathus striatus. The experiment design procedure is based either on the trajectory difference between measured data and fitted model alternatives or on the parameter distance of the two parameter sets which are identified from the two experiments. For the latter purpose, a measure for the distance between two normal distributions was derived which is defined as the minimal Mahalanobis distance that any parameter vector may have to both distributions at the same time. This definition gives the opportunity to calculate an optimal mean value for the identified parameters of the two experiments, too.

S. NIKITIN :

Stabilizability of Nonlinear Systems

The degree theory is used to prove necessary conditions of stabilizability in the large by a smooth feedback. With the help of normalizing transformations of Poincaré the sufficient conditions of local stabilizability are proved for the nonlinear system with degenerate linearization. The local stabilizer design procedure based on normalizing transformations of Poincaré is proposed. The sufficient conditions for local stabilizability of a bilinear system have been given and the appropriate stabilizing feedback has been designed. The criteria for the smooth feedback stabilizing a smooth nonlinear system locally to have smooth (piecewise smooth) extension, which stabilizes the system over a given compact set, have been obtained.

H. A. NOUR-ELDIN :

Strategische Punkte und strategische Zustände optimaler Trajektorienscharen

In der Optimierung dynamischer Systeme bleibt das Interesse zu sehr an der Optimalität einzelner optimaler Trajektorien haften. Nach der Eigenschaft, die eine optimale Trajektorienschar besitzen kann, wurde verhältnismäßig selten gefragt. Im Vortrag wird exemplarisch für lineare dynamische Systeme mit quadratischen Zielfunktionen gezeigt, daß die optimale Trajektorienschar spezifische feste Zeitpunkte und Zustände besitzen kann, die zu Recht als strategische Zeitpunkte bzw. strategische Zustände der Schar bezeichnet werden können. Nach der Bestimmung solcher strategischer Punkte und Zustände wird der Zusammenhang zwischen dem Gewichtungsparameter der Zielfunktion und den strategischen Zeitpunkten der Schar erläutert.

G. J. OLSDER :

From Linear Difference Equations to Synchronized Flow Systems

The starting point for the lecture is the finite dimensional linear difference equation $x(k+1) = Ax(k)$. The conventional operations used, addition and multiplication, are replaced by maximization and addition, respectively. In the sense of the new underlying max-plus algebra the equation $x(k+1) = Ax(k)$ can be viewed as a discrete event dynamic system; it describes the synchronization of discrete flows on networks.
Continuous analogues of such systems are given and well known results of discrete event dynamic systems (such as eigenvalue versus maximum cycle mean, relation to timed Petri nets) are extended to such systems. Thus it is shown that the synchronization aspect of such systems is much more basic than their discrete or continuous character.

A. V. SARYCHEV :

Sufficient Optimality Conditions for Pontryagin Extremals

An optimal control problem for an affine control system is investigated. We look for conditions for L_1-local optimality of a given control $\tilde{u}(\cdot)$. We start with the Pontryagin Maximum Principle which selects some controls –

Pontryagin Extremals — among which are all the optimal ones. We assume that such extremal consists of bang-bang and singular arcs separated by switching points. Introducing an extension of the 1st and 2nd variation we obtain 1st and 2nd order optimality conditions for bang-bang Pontryagin extremals. Developing Legendre-Jacobi-Morse type theory for the extended variation, we prove Index and Nullity Theorems and derive 2nd order sufficient optimality conditions for several types of Pontryagin extremals.

H. SCHÄTTLER :

Reachable Sets and Time-optimal Synthesis

Employing a Lie-algebraic formalism, the precise structure of the small-time reachable set from a reference point p as a CW-complex can be determined for control-linear systems in low dimensions under nondegenerate conditions on the Lie brackets of the vector fields at p . By constructing the small-time reachable set in an extended state-space where time has been added as extra coordinate, the precise structure of the small-time reachable set gives necessary conditions for time-optimality. These typically improve on those which can be proved using variational methods alone. By projecting along the time-coordinate, a local regular synthesis of time-optimal controls can be constructed.

E. D. SONTAG :

Systems Combining Linearity and Saturations, and Relations to "Neural Nets"

The lecture deals with control systems consisting of linearly interconnected integrators (or delay lines) and scalar nonlinearities. For linear systems with saturating sensors, we mention results on observability and minimal realization. When saturations appear in actuators, questions of control become of interest, and we describe stabilization techniques. If there are feedback loops containing the nonlinearities, "recurrent neural nets" are obtained, and we discuss various issues relating to their computational power and identifiability of parameters. Parts of the work surveyed here were jointly pursued with Francesca Albertini, Renêe Schwarzschild, Hava Siegelmann, Hêctor Sussmann, and Yudi Yang.

H. J. SUSSMANN :

How to Find Nice Necessary Conditions for Optimality If You Know What You Want Them for

High-order necessary conditions for optimality can be used in many ways to get information beyond that provided by the classical Maximum Principle. A research program based on the systematic use of subanalytic sets and stratifications has led to a general theorem that says that a "regular synthesis" exists provided that a certain class of optimal trajectories exists. (Precisely, there should exist a "sufficient family" which is "finite-dimensionally analytically parametrized" and proper.) When one tries to apply this theorem to particular optimal control problems it turns out that, in order to construct a class with the desired properties, one needs to prove that certain extremals cannot be optimal. To do this, one has to establish high-order necessary conditions for optimality. Thus, the research program tells us exactly what new conditions one needs in order to get the desired class. We show, in a number of examples — subriemannian geometry, linear time-optimal control, the "Reeds-Shepp car" — how these new conditions actually turn out to be true.

J. C. WILLEMS :

Feedback in a Behavioural Context

A definition is put forward for regular and singular feedback interconnection. For linear systems regular feedback is equivalent to the condition that the number of output and state variables is equal to the sum of output and state variables in the plant and the controller. In this context, the design of a feedback compensator reduces to the choice of a suitable subsystem of the plant. Pole placement results were reviewed form this vantage point.

Q.-H. WU :

Decentralized robust stabilization using H^{∞}-optimization

The problem of designing a decentralized controller to robustly stabilize q interconnected unstable subsystems is considered. The solution can be subdivided into three steps. First, the parametrization of stabilizers is used separately for each subsystem, without considering the interconnection. Then, the concept of quasi-block diagonal dominance is used to investigate the stability of the overall system, which leads to minimizing the Perron-Frobenius eigenvalue of a non-negative matrix. It is shown that the decentralized controller, composed of the q local H^{∞}-optimal stabilizers, is the solution to the minimization problem. A sufficient stability condition is found and a class of interconnected systems is characterized. For this class, H^{∞}-optimal stabilizers can be implemented separately for each subsystem to achieve stability of the overall system, as if the system were decoupled. Finally, it is shown that the overall system remains stable if the perturbations are bounded above by some functions of the controller.

V. BLAGODATSKIKH :

Optimal Control Problems with State Constraints

We consider the optimal control problem for a system whose behaviour is described by a differential inclusion $\dot{x} \in F(x)$. For the state $x(t)$ of the system we have state constraints $x(t) \in X$. For this problem the maximum principle of Pontryagin's type is obtained. But this maximum principle may be trivial. It means that the absolutely continuous part of the adjoint function $\psi(t)$ may be equal to zero and only the adjoint measure is nonzero. Under the assumption of so-called local controllability of the solution $x(t)$ on the boundary of the state constraint X we can prove that the absolutely continuous part of the adjoint function is nontrivial.

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