MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 12/1994

Regelungstheorie

20.03. - 26.03.1994

Die Tagung fand unter Leitung von H.W. Knobloch (Würzburg) und M. Thoma (Hannover) statt. Ein Schwerpunktthema war für die Tagung nicht festgelegt worden, so daß die gewählten Vortragsthemen bis zu einem gewissen Grad die derzeit aktuellen Forschungsaktivitäten des Teilnehmerkreises auf dem Gebiet der Regelungstheorie widerspiegeln. Etwa zwei Drittel aller Vorträge lassen sich mindestens einem der beiden Themen "Regelung nichtlinearer Systeme" und "Robustheit durch Regelung" zuordnen. Jedes dieser beiden Themen war bereits früher einmal Schwerpunktthema einer Regelungstheorie-Tagung gewesen. Neu war, daß jetzt mehrere Vorträge über Ergebnisse berichteten, die beide Themen verknüpfen, also die Robustheit gezielt als zusätzliche Anforderung in eine nichtlineare Regelung einbeziehen. Es war allgemeiner Konsens, daß diese Entwicklung den Erfordernissen der regelungstechnischen Praxis entgegenkommt und in seiner theoretischen Ausgestaltung für die Zukunft noch einiges erwarten läßt.

Eine eher kritische Auseinandersetzung fand dagegen der Umstand, daß neuere theoretische Ergebnisse, auch wenn sie aus der Sicht der Anwendung sehr attraktiv sind, typischerweise nicht zugleich schon als praktikables Entwurfswerkzeug für den Ingenieur anzusehen sind. Gefragt sind hier zusätzlich Anwendungsbreite (für eine größere Systemklasse), Anwendungstiefe (im Sinne einer ausreichenden Flexibilität, auch tatsächlich alle im Einzelfall wesentlichen Systemeigenschaften gezielt einbeziehen zu können) und schließlich eine problemlose Berechenbarkeit.

Zum Thema nichtlineare Regelung mit Robustheit führte A. Isidori die Lösung der betrachteten Regelungsaufgabe auf bekannte Ergebnisse der 2 Personen-Nullsummen-Differentialspiele zurück. Notwendige und hinreichende Bedingungen für die Existenz von worst case H_∞-Reglern und Filtern für nichtlineare Systeme waren Gegenstand des Vortrags von A.J. Krener. Eine interessante Gegenüberstellung der Set-Valued und H_∞ Techniken gab A.B. Kurzhanski, der einen verallgemeinerten Hamilton-Jacobi-Bellmann-Isaacs-Formalismus vorstellte, mit dem sich beide Lösungen berechnen lassen.

Für eine Klasse affiner Systeme behandelte K.G. Wagner die robuste Stabilisierung durch ein einfacher zu lösendes, modifiziertes Problem mit nachfolgender Approximation. Eine Erweiterung auf exponentielle Ausgangsregelung beschrieb R. Liestmann. F. Allgöwer kam anhand von Beispielen zu dem Schluß, daß die nichtlineare H_∞ Theorie als praktisches Entwurfswerkzeug noch nicht einen der linearen H_∞-Theorie vergleichbaren Entwicklungsstand erreicht hat, und C.W. Scherer zeigte für das lineare

H_2/H_∞-Problem, wie man numerisch verifizieren kann, ob ein rationaler optimaler Regler existiert. J. Ackermann präsentierte eine robust entkoppelnde Regelung für ein Fahrzeug, und S. Engell betonte in seinem Vortrag über zeitoptimale Regelung die generelle Bedeutung der Robustheit für einen praktischen Entwurf.

Im Rahmen der Lie-Bäcklund Transformation gewisser unendlich-dimensionaler Mannigfaltigkeiten diskutierte M. Fliess nichtlineare Regelungsprobleme und zeigte, daß jedes System das durch dynamische Rückkopplung linearisierbar ist, auch "flach" ist. Für die Stabilisierung nichtlinearer Systeme in Chained Form, die einen unstetigen Regler erfordern, schlug H. Nijmeijer eine Kombination aus kontinuierlicher Regelung und Abtastregelung vor und zeigte am Beispiel eines mobilen Roboters, daß dennoch sehr glatte Stellverläufe erzielbar sind. Dagegen benutzte V. Utkin die Unstetigkeit schaltender Zweipunktregler gezielt als Mittel, um Robustheit zu erzeugen. Robustheit bereits aus der Sicht der Modellierung ist gefragt, wenn nur quantisierte Messungen verfügbar sind. J. Lunze zeigte, daß hier ein nichtdeterministischer Automat als Modellierungsgrundlage für weitere regelungstechnische Betrachtungen geeignet ist.

Im Vergleich zur Reglung zeigt sich das Problem der Zustandsbeobachtung nichtlinearer Systeme viel schwieriger zugänglich. M.L.J. Hautus gab eine detaillierte Analyse der Beobachtbarkeit für lineare Systeme mit Sättigung am Ausgang. Eine spezielle Block-Dreiecks-Beobachternormalform für nichtlineare Systeme sowie notwendige und hinreichende Bedingungen für deren Existenz, stellte M. Zeitz vor. Diese Normalform gestattet die Konstruktion exponentieller Beobachter mit Methoden aus der linearen Theorie. D. Flockerzi präsentierte einen Zugang zur Beobachterkonstruktion für affine Systeme und widmete sich dabei insbesondere einigen nicht-lokalen Problemen auf der Grundlage nicht-lokaler Integralmannigfaltigkeiten, die attraktiv sind und eine asymptotische Phase zulassen.

Ganz offensichtlich hat das Ergebnis von V.L. Kharitonov über die Stabilität von Intervallpolynomen dem Gebiet der parametrischen Robustheitsanalyse linearer Systeme einen wesentlichen neuen Impuls gegeben. V.L. Kharitonov selbst berichtete über eine Klasse nichtlinearer Parameterunsicherheiten, für die die Robustheitsanalyse ebenso einfach wie für den affinen Fall ist. Konische Parameterunsicherheiten betrachtete D. Hinrichsen, während F.J. Kraus sich mit elliptischen Unsicherheiten, wie sie bei der Parameteridentifikation auftreten, befaßte. K.R. Schneider untersuchte die Bifurkation der Stabilität in Evolutionsgleichungen und deren Kontrolle durch glatte Rückkopplungen.

Eine andere Möglichkeit Robustheit zu erzielen, liegt in der selbsttätigen Adaption. Für lineare Regelstrecken präsentierte A. Ilchmann adaptive Regler nach dem Prinzip der hohen Verstärkung, welches die Identifikation von Parametern vermeidet, aber stabile Übertragungsnullstellen voraussetzt. Dagegen stellte G. Kreisselmeier einen auf zwei klassische Identifizierer gestützten adaptiven Regler vor, der nur noch Stabilisierbarkeit und die Kenntnis einer oberen Schranke für die Ordnung der Regelstrecke benötigt.

Besondere Aufmerksamkeit erhielten zwei Vorträge über Anwendungen in der Medizin. G. Vossius berichtete über Patienten, bei denen durch zentrale Lähmungen eine Spastik auftritt, und wie man versucht, die angenommene fehlerhafte Selbstorganisation des Neuronennetzwerkes des Rückenmarkes durch Elektrostimulation umzuprogrammieren und für eine normale Funktionsausübung zu öffnen. F. Kappel erläuterte Arbeiten, deren Ziel ein Modell zum klareren Verständnis der Vorgänge ist, die bei der Reaktion des kardiovaskularen Systems auf eine kurzzeitige ergometrische Belastung auftreten. Angesichts der enormen Schwierigkeiten der Modellierung und der Notwendigkeit, mit kaum beweisbaren Hypothesen zu arbeiten, hat die konsequente Verwendung neuester regelungstheoretischer Methoden für den über viele Jahre aufgebauten Erfolg dieser Arbeiten einen besonderen Stellenwert.

H.J. Sussmann stellte eine strenge Version des Maximumprinzips von Pontryagin unter der schwachen Voraussetzung vor, daß $f(x, u, t)$ stetig in x und ein "Referenz-Vektorfeld" lokal Lipschitz ist. Der Kern des Beweises ist ein Open Mapping Theorem for Set-Valued Maps. Abnormale Extremalen in Lagrange'schen Variationsproblemen diskutierte A.V. Sarychev und gab Bedingungen zweiter Ordnung für schwache Minimalität und Rigidität, d.h. Isoliertheit des extremalen "Punktes" an.

H. Kwakernaak zeigte, indem er äquivalente Zustandsraummodelle für Polynommatrizen einführte, wie man polynomiale Algorithmen aus der linearen H_2 und H_∞ optimalen Regelung durch numerisch vorteilhaftere Zustandsraumalgorithmen ersetzen kann. Eine ganz andere Art des numerischen Berechnens betrachtete U. Helmke, indem er das gesuchte Ergebnis als stabile Ruhelage eines dynamischen Systems darstellte.

Motiviert durch Anwendungen in der Signaltheorie, Sprachsynthese und der stochastischen Realisierungstheorie gab C.I. Byrnes eine vollständige Charakterisierung aller Kovarianzfolgen, die positiv und rational sind. H. Wimmer untersuchte die Menge aller positiv-semidefiniten Lösungen der algebraischen Riccati-Gleichung, und G.J. Olsder berichtete über notwendige und hinreichende Bedingungen für die Existenz eines stationären Verhaltens in Min-Max-Systemen. Eine deterministische Fassung von Oseledec's Satz für lineare gewöhnliche Differentialgleichungen mit beschränkten, zeitvariablen Koeffizienten gab F. Colonius.

D. Bothe präsentierte eine explizite Darstellung der offen erreichbaren Mengen für ein Kontrollproblem von H. Hermes, und D. Franke sprach über Beobachtung und Regelung arithmetisch linearer Finite State Machines. Die Komplexität der Modellbildung bei mechatronischen Systemen waren das Thema von J. Lückel, und P.C. Müller gab einen Überblick über regelungstechnische Besonderheiten bei Descriptor-Systemen.

Nur am Rande sei aus den historischen Anmerkungen der Tagungsleiter die amüsante Feststellung über menschliche Wesensart notiert: "The higher in rank, the more observable, the less controllable".

Die Tagung Regelungstheorie ist in Deutschland die einzige, die gezielt Mathematiker und Ingenieure auf diesem Gebiet miteinander konfrontiert. Der Trend der vergangenen Jahre, daß sich Gedankenaustausch und Zusammenarbeit von Mal zu Mal intensivieren, setzte sich fort. Das Interesse und die Beteiligung aus dem Ausland (etwa ein Drittel der Teilnehmer) waren auch dieses Mal ein sicheres Zeichen für Vielseitigkeit und gutes Niveau der Tagung.

J. ACKERMANN

Robust Car Steering

Conventionally the driver of a car commands a front wheel steering angle. The resulting motion depends on velocity, mass, road-tire contact and other uncertain positive parameters. In a robust steering system the driver commands a lateral acceleration a_f at a point in the front part of the car. This acceleration follows almost exactly the command a_{fref} no matter what the parameter values are. Such a robust steering system is derived in two steps:

i) Feedback of yaw rate and lateral acceleration at two points provides triangular decoupling of two subsystems: a) a steering subsystem involving only the unknown front-wheel tire characteristics, its state is a_f, and b) a jaw subsystem involving only the unknown rear-wheel tire characteristic. It is shown that the jaw subsystem is stable and not observable from a_f.

ii) Feedback of a_f provides an ideal steering behavior $a_f \approx a_{fref}$.

The driver directly applies a lateral acceleration a_f to a mass point in the front part of the car in order to keep it on top of his planned path. He does not have to care about jaw motions or parameter changes.

F. ALLGÖWER

Practical Controller Design by Nonlinear H_∞-Minimization — Delights and Woes —

Since several years linear H_∞-control theory experiences remarkable popularity in engineering applications. The main reasons for this are the possibility to explicitly include robustness considerations in the design and the fact that there is a very transparent relation between physical performance objectives and H_∞ loop-shaping design specifications. During the last couple of years a theory for nonlinear H_∞-minimization was developed as an extension to the linear theory. In our presentation we critically examine whether nonlinear H_∞ provides a framework equally well suited for practical controller design as its linear analog. Some practically interesting nonlinear H_∞ design problems are shown and areas are pointed out where, from an engineering point of view, there is still need to further develop the underlying mathematical theory.

D. BOTHE

A Control System with Open Attainable Sets

In his paper "On the Structure of Attainable Sets for Generalized Differential Equations and Control Systems" (J.Diff. Eqs. 9, 141 - 154, 1971) H. Hermes gave an interesting example of a two-dimensional control system $x' = \rho(x)u$, $u \in U$ with Lipschitz continuous ρ and compact U, having open attainable sets $P(t)$ for all $t > t_0$.

Based on this example we give an improved version which, in addition, also allows a thorough analysis of the attainable sets. In particular, we get the representation

$$P(t) = \{(r\cos\theta, r\sin\theta) : 0 \leq \theta < 2\pi, 0 \leq r < R(t,\theta)\} \text{ for } t > 1 + \sqrt{2}.$$

and by computation of the time optimal solutions of the convexified problem the inverse of $R(\bullet, \theta)$ can be given explicitly.

C.I. BYRNES

Parameterization of Covariance Sequences

In this talk, we describe a recent characterization, due to Lindquist, Gusev, Mateev and the presenter, of all positive rational extensions of a given partial covariance sequence. This result, which proves a conjecture due to Georgiou, has a long history beginning with an application to potential theory by Caratheodory and Schur. Our research on this problem is motivated by its applications to signal processing, speech synthesis and stochastic realization theory. This characterization is in terms of a complete parameterization using familiar objects from systems theory. The methodology employed is a combination of complex analysis, geometry, linear systems and the theory of nonlinear dynamical systems as applied to certain filtering algorithms.

F. COLONIUS

Lyapunov Exponents, Stabilization and the Hamilton-Jacobi-Equation

For families of linear ordinary differential equations with bounded time-varying coefficients, a deterministic analogue of Oseledec's Theorem is proven. The result is based on an analysis of chain recurrence in an associated linear flow on a vector bundle and geometric nonlinear control for an associated system on projective space. This has applications to stabilization of bilinear control systems. Here the minimal Lyapunov exponents can be approximated by the value functions of discounted optimal control problems, which can be solved via the Hamilton-Jacobi-Bellman equation. The theory is illustrated by numerical results for 2- and 3-dimensional systems.

S. ENGELL

Towards Applicable Time-Optimal Control

It is, in general, desirable that controllers use the available power of the actuators fully. Time-optimal control achieves this whereas linear controllers in most cases are designed such that large actuator amplitudes are reserved for the largest possible control errors and hence are used almost never, hence they are inefficient. On the other hand, time-optimal controllers show severe deficiencies which prevent their practical application: high sensitivity to measurement noise and errors in the plant model, large transient errors of fast variables in multivariable control. Moreover, on-line computation is not feasible in most cases.

In this talk, some remedies to these problems are discussed which bring time-optimal control closer to applicability: speed-up of the on-line computation, output regulation, min-max-rest control and embedding of linear controllers. Further, it is demonstrated that relatively simple nonlinear controllers can provide robust approximately time-optimal control under realistic conditions. This poses the interesting problem of a theoretical investigation of such schemes, esp. of the trade-off between closeness to optimality and robustness.

M. FLIESS

Flatness and Differential Geometry

In this joint work with J. Lévine, P. Martin and P. Rouekou, nonlinear control and dynamic feedback linearization are discussed within the framework of Lie-Bắcklund transformations of some infinite-dimensional manifolds. It is shown that any system which is dynamically feedback linearizable is flat. Time scaling is shortly discussed. Controllability is interpreted via Vinogradov's variational complex.

D. FLOCKERZI

Observers for Affine Control Systems

We present an approach of constructing observers for nonlinear control systems. Thereby we attempt to give answers to some non-local problems for affine control systems. The main tool hereby is the theory of non-local integral manifolds that are attractive and allows an asympotic phase. The control input will be used first to generate the necessary dichotomy for the existence of such an integral manifold and secondly to establish the desired performance of the reduced system on this manifold. We present applications to problems of stabilization and parameter estimation and address the non-local error feedback regulator problem.

D. FRANKE

Observer-Based Control of Arithmetically Linear Finite State Machines

The contribution addresses discrete systems with a finite number of states which can be modelled by the state equations of a finite automaton. In contrast to traditional work, the approach is based on *arithmetic* representations of Boolean functions appearing on the right hand side of the underlying finite state equations. This allows a unifying view on discrete-event systems and classical discrete-time systems. The presentation focusses on the special class of arithmetically *linear* finite state machines. The design of feedback control using reduced observers is extended to this class of systems. Incompletely specified machines which allow only a subset of possible states and controls will be included. Using sensor coordinates, the reduced observer design is a straight forward extension of the classical discrete-time case, eigenvalue assignment playing a central role. The procedure will be illustrated by means of an example.

M.L.J. HAUTUS

Observability of Saturated Systems

The observability is investigated of a linear time-invariant system in which the output can only be measured via a saturation device of the form

$$\begin{aligned} z(t) &:= y^+ \quad (y(t) \geq y^+) \\ z(t) &:= y(t) \quad (y^- < y(t) < y^+) \\ z(t) &:= y^- \quad (y(t) \leq y^-). \end{aligned}$$

Obviously, the observability of the original system is a necessary condition for the observability of the saturated system. So this is a standing assumption in the talk. In addition, only single-output systems are considered.

The observability properties of the saturated system depend on the restriction set U for the input variable and on the location of the origin (in y-space) w.r.t. the interval $Y := (y^-, y^+)$. As to the set Y, distinction has to be made between the cases $0 \in Y, 0 \in \bar{Y} \setminus Y$ and $0 \notin \bar{Y}$. Three cases are also distinguished for the input set U: the *free-input* case $U = \mathbf{R}^m$, the *zero-input* case $U = \{0\}$, and the *small-input* case, where $0 \in \operatorname{int} U$ and U is bounded. In the free-endpoint case, the saturated system is always observable. In the zero-input case, observability conditions for the saturated system are expressed in terms of the eigenvalues of the system matrix A. The situation is more complicated in the small-input case. In that case only the strictly dominant eigenvalues of A have influence in the observability. Specifically, they are not allowed to be real and positive if the saturated system is to be observable.

U. HELMKE

Dynamical Systems Methods in Numerical Analysis and Control

In this talk I explain how problems from numerical analysis and control theory can be solved using gradient flow methods. Dynamical systems are considered whose solutions converge to equilibria points, which yield the solutions to various computational tasks such as:

- The diagonalization of matrices
- Total least squares estimation
- Output feedback control problems such as pole assignment.

The main part of the talk will concentrate on a classical as well as new approach to pole placement via gradient flow methods.

D. HINRICHSEN

Stability of Polynomials with Conic Uncertainty

Let P_n be the vector space of real polynomials of degree $\leq n$, and suppose that $p_0 \in P_n$ is Hurwitz stable, $K \subset P_n$ a convex cone. We derive various necessary and sufficient criteria for $p_0 + K$ to be Hurwitz (consist only of Hurwitz stable polynomials). In particular, if K is a polyhedral cone generated by an interval polynomial then $p_0 + K$ is Hurwitz if and only if (i) the associated four Kharitonov polynomials $p_1, \ldots, p_4$ and $\sum_1^4 p_i$ are semistable and (ii) the four rays $p_0 + \mathbf{R}_{p_i}$ are stable. The latter stability can be tested by solving four algebraic equations.

The paper is based on joint work with V.L. Kharitonov.

A. ILCHMANN

Non-Identifier-Based High-Gain Adaptive Control

We consider a class $\sum$ of multivariable systems of the form

$$\begin{aligned} \dot{x}(t) &= A\,x(t) + B\,u(t) \\ y(t) &= C\,x(t) \end{aligned}$$

where $A \in \mathbf{R}^{n\times n}, B, C^T \in \mathbf{R}^{n\times m}$. The state dimension n as well as the entries of the matrices are unknown. The only structural assumptions are:

(i) (A, B) is stabilizable by state feedback,

(ii) (A, C) is detectable,

(iii) $C(s\,I_n - A)^{-1}B$ has no zeros in $\{s \in \mathbf{C} \,|\, Re\, s \geq 0\}$,

(iv) $\det(C\,B) \neq 0$.

For $\sum$ and a fairly rich class of reference signals γ_{ref} the control objective is as follows: Let $\lambda > 0$ be given. Design a feedback mechanism $u(t) = f_\lambda(y_{ref}(\cdot), y(\cdot))$ such that for arbitrary $(A, B, C) \in \sum$ and $y_{ref}(\cdot) \in \gamma_{ref}$ the output $y(t)$ of the nonlinear closed-loop system tracks $y_{ref}(t)$ asymptotically within the closed ball of radius λ centered at 0, i.e.

$$||y(t) - y_{ref}(t)|| \longrightarrow \{\eta \in \mathbf{R}^m \,|\, ||\eta|| \leq \lambda\} \text{ as } t \to \infty.$$

A. ISIDORI

Regulation and Tracking for Nonlinear Systems in the Presence of Gain-Bounded Uncertainties

In this paper, we study the problem of designing a feedback law which internally stabilizes a nonlinear system and simultaneously achieves asymptotic tracking of a prescribed set of reference trajectories, in the presence of modeling uncertainties. The problem is addressed in the following way. First of all, we show how a problem of robust asympotic tracking (in the prescence of modeling uncertainties) can be reduced to a problem of robust stabilization of a suitable augmented system, which includes the original controlled plant as well as an internal model of the exogenous system which is supposed to generate the required reference trajectories. Then, we address the problem of robust stabilization of this augmented system and we show how this problem, in the light of the celebrated "small gain theorem", can be reduced to a problem of internally stabilizing a system and simultaneously rendering the "gain" between certain inputs and outputs lower than a prescribed bound. The solution of the latter, which in fact is a (sub)optimal problem of disturbance attenuation with internal stability, can be obtained by appealing to some standard results in the theory of two-person zero-sum nonlinear differential games.

F. KAPPEL

Feedbacklaws in Cardiovascular Modeling

The basic goal of the modeling efforts presented here is to obtain a clear understanding of the mechanisms which govern the reaction of the cardiovascular system to a short term ergometric workload. In the long run the model should be used to identify parameter sets which characterize the state of the cardiovascular system of an individual person.

Another long term goal is to improve the control actions of pacemakers in reaction to short term workloads.

The model presented is based on Grodins' model for the mechanical part of the cardiovascular system. The feedback law realized by the baroreceptor loop is modeled assuming that a quadratic cost functional is minimized. The model also includes a submodel for the process of autoregulation. Using an output-least-squares formulation is was possible to identify 16 unknown parameters in the model using measurements for the mean arterial pressure in the systemic circuit and for the heart rate. The measurements were obtained through bicycle ergometer tests. The resulting model gives a very acceptable fit to the date and also provides physiologically reasonable values for the other state variables. The results presented here are joint work with R.O. Peer and appeared in J. Math. Biology, Vol. 31, 1993.

V.L. KHARITONOV

Robust Stability (Parametric Appraoch)

The problem of robust stability of families of polynomials was studied. First some basic results for affine parametric uncertainties were exposed. Then it was shown how these results can be adapted for the case of nonlinear parametric uncertainty. The main goal of the talk can be formulated as follows: It was shown that there exists the teach class of nonlinear parametric uncertainties for which robust stability analysis is as simple as for the affine case.

F.J. KRAUS

Robust Control with Elliptical Uncertainty

A design method for robust controllers for a class of uncertain dynamical systems is presented. More precisely, the method consists of

- modeling of the parametric, structural uncertainty as an elliptical region (obtainable from the identification directly)
- value set concept
- zero exclusion principal
- family of elliptical D-stability domains
- expansion factor of the uncertainty (preventing the D-stability)
- numerical optimization of the parameter expansion factor w.r.t. the controller parameters.

Under this set up the expansion factor is a real rational function, which is used extensively during the optimization. The method can be extended to uncertainty of controller parameters also. In this case we obtain a conservative approximation only.

G. KREISSELMEIER

Parameter Adaptive Control: A Solution to the Overmodeling Problem

The adaptive regulation of linear time-invariant plants with unknown parameters gives rise to the so-called overmodeling problem, when the plant is of lower order than assumed ($n_p \leq n, n$ being a known upper bound). Martensson (1985) showed the existence of a smooth solution to the problem by constructing a controller combined with a self-organized search in the space of controller parameters, which is dense and arbitrarily slow almost everywhere. In contrast to this mathematical result, a solution to the overmodeling problem is given here in terms of a smooth, descent oriented parameter adaptive controller in the classical engineering sense.

A.J. KRENER

Necessary and Sufficient Conditions for Nonlinear Worst Case (H-Infinity) Control and Estimation

We present necessary and sufficient conditions for the existence of worst case controllers and estimators for nonlinear systems. These are also called H-infinity suboptimal controllers and estimators. We consider affine and more general nonlinear systems, both time varying and autonomous over finite, semi-infinite and infinite intervals. In particular, we give necessary and sufficient conditions for the solvability of a standard H-infinity suboptimal control problem by measurement feedback that involve the solvability of a pair of partial differential equations of the Hamilton-Jacobi type. The first is the one associated with the problem of H-infinity suboptimal control by state feedback that has appeared previously in the work of several authors. The second is a new Hamilton-Jacobi equation associated with H-infinity suboptimal estimation.

A.B. KURZHANSKI

On Two Approaches to the Treatment of Uncertainty in Nonlinear Filtering and Control (The Set-Valued and the H_∞-Techniques — Two Sides of One Medal?)

The lecture deals with the connections between the set-valued approach to modelling uncertain dynamics (through the theory of differential inclusions, viability and guaranteed estimation techniques) and the so-called H_∞ approach. If the set-valued approach gives a precise set-valued estimate of the errors in the system performance under unknown but bounded uncertainties, the nonlinear H_∞ approach usually gives a single-valued solution with no a priori bounds on the uncertain items and no precise estimates on the performance or estimation errors.

This lecture indicates a generalized Hamilton-Jacobi-Bellmann-Isaacs (HJBI) formalism that allows to calculate both the single-valued H_∞ solution (as the global extremum of the viscosity solution for the related HJBI equation) and the set-valued solution (as the level-set for the same function) which gives the error bounds on the system performance. The problems are treated for a finite time-interval.

H. KWAKERNAAK

State Space Algorithms for Polynomial Operations in System Theory

Polynomial matrices have important applications in linear system and control theory. Examples are the behavioral theory of linear systems and H_2 and H_∞ optimal regulation. Polynomial algorithms have a reputation of numerical unreliability, as opposed to state space algorithms. The purpose of this project is to develop state space algorithms for polynomial matrix operations. The basic idea is to associate with a given polynomial matrix P the "behaviour"

$$P(\frac{d}{dt})\, w(t) = 0 \ , \ t \in \mathbf{R}.$$

After finding a state space representation for this behaviour the desired manipulations are done in state space. Back transformation to polynomial form yields the desired result. Examples of problems that may be solved this way are factorization of polynomial matrices (including J-spectral factorization), computation of the zeros of a polynomial matrix, and the computation of the null space of a polynomial matrix. Also one- and two-sided linear polynomial matrix equations may be solved by these methods.

R. LIESTMANN

Full Information Regulator for Nonlinear MIMO Systems

Assume a system with the same number of inputs and outputs, an exogenous signal w which may enter the system, in general in a nonlinear way. The outputs will depend only on the state of the plant. My control should be chosen such that:

(i) $x = 0$ is an asymptotically stable equilibrium of the unperturbed plant.

(ii) The closed-loop admits an invariant manifold having a representation on $x = \pi(t, w)$ which annihilates the output, i.e. $h(\pi(t, w)) = 0$.

(iii) This manifold is a global attractor, i.e. $x(t) - \pi(t, w) \rightarrow 0$ exponentially as $t \rightarrow \infty$.

Hypothesis:

1) The system (with state (x, w)) has a well defined relative degree.

2) The control laws are not present in the zero dynamics, i.e. span $\{g_1(x), \ldots, g_n(x)\}$ is involutive.

Proceed in two steps

1) Construction of an invariant manifold for the zero dynamics of the system.

2) Show that by adequate choice of the control functions this invariant manifold is an exponential attractor.

The continuation idea of this work is to leave the 2nd hypothesis away, i.e. the control will be present in the zero-dynamics. In this case we will proceed as follows:

Extend the initial system by adding Lie-brackets of the original g_i (and new control functions), suppose that after the first iteration of the Lie-brackets of all the g_i, we reach full state dimension. Then we are able to solve for this entended system the full information regulator problem, and we "go back" to the original system by using the "shadowing Lemma" from K. Wagner, which allows us to construct the control functions of the original system.

J. LÜCKEL

Mechatronics, Modelling of Mechanical Systems

Mechatronic systems consist of components from different technical disciplines. They require an integrated design of all components. This leads to systems of high complexity, with the mechanical and information processing components at the centre. The modelling systematics presented here allows an easy and flexible exchange of any desired mechanical subsystems on the basis of their dynamical equations, using the rigid multy body approach. This way of modelling considerably facilitates analysis and synthesis of complex systems and supports distributed digital simulation oriented according to the physical structure.

J. LUNZE

Qualitative Control of Continuous-Variable Systems

Qualitative control concerns the situation where the feedback controller receives only a quantised measurement $[y(k)]$ of the system output $y(k)$. For example, it is only known in which interval the output currently resides. This is the reason why the difference equation, which governs the dynamical system does not provide a reasonable description of the plant for the purpose of controller design. Instead, a nondeterministic automaton is used as qualitative model of the plant.

The main results of this paper show that qualitative controllers can be designed by means of this qualitative model and that important system properties such as the stabilizability of the plant and the stability of the closed-loop system can be proved by means of the qualitative model and without knowledge of the differential equations.

P.C. MÜLLER

Control of Descriptor Systems

In the last decade the investigation of descriptor systems (singular systems, differential-algebraic equations) has been increased essentially. One reason for the redundant formulation of dynamical systems is its better physical transparency and its interpretation by subsystems. Compared with common methods available for investigating usual state space systems many problems still have to be solved making also available a complete set of tools to analyse, to design and to simulate descriptor systems. In this contribution a survey is given on the identification of descriptor systems, on the stability analysis, on the linear quadratic optimal control design and on the observer design. All these aspects are explained additionally in case of mechanical descriptor systems. It is shown that all the problems have to be considered carefully to avoid inconsistencies or contradictions. Actually, all the new tools for dealing with descriptor systems are implemented as a MATLAB toolbox.

H. NIJMEIJER

Practical Stabilization of Nonlinear Systems in Chained Form

This paper presents a hybrid controller for the practical stabilization of general n-dimensional nonlinear systems in one-chained form. This controller consists of two parts: 1. A discrete-time part that practically stabilizes a subset of the system states, and 2. A piece-wise continuous-time part that steers the remaining state-components to an arbitrarily small neigborhood of zero. One attractive feature of the proposed control approach is that it straightforwardly allows for generalizations in the sense that integrators can be put in cascade with the control inputs without affecting the closed-loop stability properties. This yields smoother control inputs, which makes the hybrid controller particularly useful for some relevant applications like mobile robots.

G.J. OLSDER

Min-Max systems

Systems in which the operations min, max and addition appear simultaneously are called min-max systems. Such systems, which are extensions of timed discrete event systems (which on their turn are based on the max-plus algebra, i.e. on the operations max and + only), have been studied for some years now. A classification of such systems is given and both structural and nonstructural properties are studied. The existence of (structural) fixed points for min-max systems have been studied specifically. The so-called class of bipartite systems (and their decomposition into elementary bipartite systems) turns out to be a very fruitful class of min-max systems. Necessary and sufficient conditions are given for the existence of stationary behaviour. Stability issues, eigenvalues are briefly indicated. For applications one can think of the evolution of timed Petri nets and the analysis thereof.

A.V. SARYCHEV

Abnormal Extremals in Lagrange Variational Problems and sub-Riemannian Geometry

Abnormal extremals in Lagrange variational problems including problem of relative extremum, Lagrange problem of the Calculus of Variations and problem of finding length-minimizing paths on sub-Riemannian manifolds. These are extremals which satisfy the 1st order minimality condition with vanishing Lagrange multiplier for the minimized functional. These abnormal extremal often exhibit phenomenon, called rigidity, which is isolatedness of the extremal "point" in the set determined by constraints. We establish 2nd-order weak minimality and rigidity conditions for the abnormal extremals and develop Legendre-Jacobi-Morse-type theory of 2nd variation for abnormal extremals of the Lagrange problem of the Calculus of Variations and abnormal sub-Riemannian geodesics.

C.W. SCHERER

Multiobjective H_2/H_∞ Control

For a linear time invariant system with several disturbance input and controlled output channels, we show how to minimize the H_2-norm of one of these channel's transfer matrices while keeping the H_2-norm or the H_∞-norm of the other channel's transfer matrices bounded. This can be interpreted as optimizing the nominal performance of the system while keeping bounds on H_2-norm or H_∞-norm performance or while keeping the closed-loop system robustly stable. This multiobjective H_2/H_∞-problem in an infinite dimensional space is reduced to a sequence of finite dimensional convex optimization problems by approximating, on the basis of n-width results, suitable subsets of all stabilizing controllers. This approximation scheme leads to an algorithm for computing the optimal value. As a major new application we show how to numerically verify whether a *rational* optimal controller exists. If existing, we reveal how to determine the order of the corresponding Youla parameter, and we show how the novel trick of optimizing the trace norm of the Youla parameter over suitably defined convex constraints combined with Hankel norm approximation allow to design a nearly optimal Youla parameter of the same order as and arbitrarily close to the optimal one.

K.R. SCHNEIDER

Stabilization and Bifurcation Control of Steady States in Evolution Equations

We consider evolution equations of the type (*) $F(z, \dot{z}, \lambda) = 0$ which depend on some parameter vector and define a dynamical system on some manifold. We suppose z_0 to be a steady state solution of (*) for all λ which changes its stability when λ crosses λ_0. We address the problem: Can we control the stability of the solution bifurcating from z_0 by a smooth feedback? We derive conditions by means of invariant manifolds guaranteeing the existence of such (finite dimensional) controller for parabolic systems and differential algebraic equations.

H.J. SUSSMANN

A Strong Version of the Maximum Principle Under Weak Hypotheses

The "classical" version of the Pontryagin Maximum Principle, proved in 1962 in the book by Pontryagin et al., deals with control systems of the form $\dot{x} = f(x, u, t)$, in which f is of class C^1 with respect to x. The "nonsmooth" version, due to F. Clarke (1976) deals with the more general case when f is locally Lipschitz with respect to x. Following an idea due to S. Lojasiewicz, we present an even more general version of the Maximum Principle, in which f is only required to be continuous with respect to x, and the "reference vector field" obtained by plugging in the reference control $t \to u_*(t)$ is required to be locally Lipschitz. For example: consider the system $\dot{x} = y + u\varphi(x,y)$, $\dot{y} = u(1 + \psi(x,y))$, where φ and ψ are continuous functions on $\mathbf{R}^2$ such that $\varphi(0,0) = \psi(0,0) = 0$. Assume u is constrained to satisfy $|u| \leq 1$. Is this system locally controllable from $(0,0)$? A formal application of the Maximum Principle yields an affirmative answer. However, neither the classical nor the nonsmooth version provide a rigorous justification of the formal argument, since the right-hand sides of the system equations are not locally Lipschitz. On the other hand, if we plug in the reference control $u(t) = 0$, then we get a Lipschitz (in fact C^1) vector field. Therefore our version of the Maximum Principle applies. The version presented here also incorporates high-order point variations. The proof is based on a generalization of the concept of differential that makes it possible to define "semidifferentials" at a point p of maps in a class that contains all Lipschitz maps, all continuous maps that are differentiable at one point in the ordinary sense, and even some set-valued maps. The key point of the proof is an Open Mapping Theorem for set-valued maps.

V. UTKIN

Sliding Mode Control Design Based on Ackermann's Formula

The sliding mode control methods are developed to design systems which have the desired dynamic behaviour and are robust with respect to perturbations. It is shown that the discontinuity plane for sliding mode control may be found in an explicit form using Ackermann's formula. Two design procedures are derived. First static controllers are designed to enforce sliding modes with the desired dynamic properties after a finite time interval. Then dynamic controllers are designed that exhibit the desired dynamic properties during the entire control process.

G. VOSSIUS

Konsequenzen aus der kybernetischen Organisation der Willkürmotorik für die antispastische Therapie mittels Elektrostimulation

Als eine der Folgen zentraler Lämungen tritt gewöhnlich eine mehr oder weniger ausgeprägte Spastik auf. Als Ursache für die Spastik werden direkte Veränderungen in den synaptischen Verbindungen im Neuronennetzwerk des Rückenmarkes kombiniert mit dem Wegfallen der übergeordneten Aktivierungs-Hemmungsmechanismen angenommen. Faßt man die Entstehung der Spastik als eine fehlerhafte, unkontrollierte Selbstorganisation des Neuronennetzwerkes des Rückenmarkes um alle, primitive Reflexbahnen auf, sollte es möglich sein dieses Netzwerk gegebenenfalls umzuprogrammieren und bei zeitweisen Lähmungen wieder für eine normale Funktionsausübung zu öffnen. An Beispielen der Therapie von Patienten mit Spastik mittels Elektrostimulation wird gezeigt, daß es tatsächlich möglich ist, den Status des RM von "spastisch" über "indifferent" zu geordneter Funktionsweise zu überführen. Die sich hieraus ergebenden Konsequenzen für die Mechanismen der Spastik und die daraus resultierenden therapeutischen Konsequenzen werden diskutiert.

K.G. WAGNER

Robust Stabilization for a Class of Controllable Affine Systems

Let there be given an affine control system $\sum : \dot{x} = f_0(x) + g_1(x)u_1 + \ldots + g_m(x)u_m$ with $f_0(0) = 0$ and no control constraints. We propose a robust control design for leading $\sum$ into a small neighborhood of the zero trajectory and then keeping it there ("stabilization"). To this end form an "extended system" $\sum^*$ by adjoining to $\sum$ the Lie-brackets $[g_v, g_\mu](x)$ as further controlled vector fields. Our assumption is that the $g_v(x), [g_v, g_\mu](x)$ span the whole x-space at $x = 0$ (yet there may exist no conventional smooth state feedback control law stabilizing $\sum$). The idea is to impose a robust stabilizing control law on $\sum^*$ (which is easy) and then to approximate the resulting $\sum^*$ trajectories by $\sum$ trajectories. An algorithm is available for the construction of suitable $\sum$ controls out of the $\sum^*$ control. The $\sum$ control generally takes on large values but can be made to meet a prescribed bound once a sufficiently small neighborhood of 0 is reached. To avoid error accumulation and for the sake of robustness a state feedback at discrete times is incorporated into the $\sum$ control law.

H. WIMMER

Semidefinite Lösungen von algebraischen Riccati-Gleichungen

Die Menge der positiv-semidefiniten Lösungen der algebraischen Riccati-Gleichung $-A^*X - XA + XBB^*X - H^*H = 0$ (ARE) wird untersucht. Nach einer geeigneten Zustandsraumtransformation zerfällt die ARE in eine Lyapunov-Gleichung und in eine Riccati-Gleichung, die nicht mehr weiter zerlegbar ist. Falls alle rein-imaginären Eigenwerte von A steuerbar sind, gibt es eine bijektive Abbildung der Menge der p.s.d. Lösungen der ARE auf eine wohldefinierte Menge von A-invarianten Unterräumen. Diese Abbildung ist zusammen mit ihrer Inversen ordnungserhaltend und stetig. Analoge Aussagen gelten für die zeit-diskrete ARE.

M. ZEITZ

Block Triangular Nonlinear Observer Normal Form

Recently in [1], a block triangular nonlinear observer normal form has been introduced which can be interpreted as a series connection of subsystems in nonlinear observer normal form. Based on this new form, exponential observers can be designed using methods from the linear case. Moreover, necessary and sufficient conditions for the existence of state transformation into this normal form have been given.

The observability normal forms with different lengths of its subsystems are the point of departure for the transformation into the block triangular observer normal form. In dependence of the polynomial structure of the characteristic observable form functions, sufficient conditions can be given for the existence and for the block triangular structure of this observer normal form. - Examples illustrate the transformation algorithm and the enlargement of the proposed nonlinear observer design method in comparison to the classical normal form approach.

[1] J. Rudolph and M. Zeitz, A block triangular nonlinear observer normal form, Systems & Control Letters 1994, to appear.

Berichterstatter: G. Kreisselmeier

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Gefördert durch
DFG Deutsche Forschungsgemeinschaft