Mathematisches Forschungsinstitut Oberwolfach

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Regelungstheorie

February 24th – March 2nd, 2002

The meeting on Regelungstheorie was organized by F. Allgöwer (Stuttgart) and H. Kwakernaak (Twente). A total of 46 participants from 13 countries did attend the meeting, showing the great international interest in this event.

The topics covered by the workshop are linear systems, nonlinear systems, distributed and delay systems, geometric control, mechatronic systems, computational aspects, robust control, and nonlinear observers.

Linear control systems were covered in two sessions with two talks in each session. The spectrum of topics covered in this area ranges from the controller design using the technique of linear matrix inequalities to polynomial methods for controller design. In the talks new theoretical results and computational approaches are presented.

The coverage of nonlinear systems was very broad, namely, three sessions were held and seven talks were given. Due to the large number of problems in nonlinear systems the topics range from bifurcation problems, stability questions, approximations, to synchronization. It can be clearly stated that the area of nonlinear systems is a very active. This statement was supported by the active presentation of a huge number of new results during this workshop. Especially new computational methods and the corresponding theory were at the forefront of the presented work. This shows the forefront, fruitful interaction between engineers and mathematicians in this very important research field of nonlinear systems.

Three important contributions were presented in the session on distributed and delay systems. This class of infinite dimensional systems is of interest from the theoretical side with respect to stability questions and with respect to controller design from the practical point of view.

Geometric control was also present in the Lie group approach to nonlinear systems and in the computational approach to the pole assignment problem, based on optimization algorithms on Grassmann manifolds. In this session a nice interplay between Lie group theory, computer algebra, and floating point computations was visible.

From the engineering point of view the design of systems in mechanical engineering is still a very hard task, especially when sensors, actuators and the corresponding control have to be designed at the same time. In the session on mechatronic systems two real world problems were presented and solved using a structured approach and modern results from algebra and group theory.

One session was dedicated to computational aspects and the authors in this session show how modern methods from convex analysis, real algebra, and the moment problem can be joined in order to solve important design and optimization problems.

In two sessions the newest results on robust control were presented. As usual in this field stability was the main concern and also controller design ensuring asymptotic stability was of utmost importance. Several new results were presented and real world experience was presented.

The very important topic of nonlinear observers was covered by two sessions with four talks presenting new approaches to the problem. This topic is so important because every feedback controller needs the state of the systems which is usually not available in practical problems and has to be reconstructed by an observer. Several new results were presented and tested in some benchmark applications. This field shows very nicely the interconnection of theoretical and computational approaches and the usage of computer algebra.

A particular highlight of the whole week was the session on open problems organized jointly by R. Sepulchre and J.C. Willems. In this session six important open research problems from mathematical systems and control theory were presented. The topics range from operator theory in Hilbert spaces to discrete event systems. Without any doubt this session was a particular success and will have a strong influence on the future research of the participants. The full papers of this session will be compiled into a book and published in the near future.

Due to the intensive discussions following each talk and due to the time schedule the personal interaction between the participants was ideal. The organizers planned a well balanced program which covers the area of Regelungstheorie and shows the very active ongoing research worldwide in this field. The workshop shows very clearly that research in Regelungstheorie is the best example of a field where mathematicians and engineers work together in order to solve important problems.

This report would not be complete without mentioning the excellent staff at Oberwolfach which creates a stimulating atmosphere in which the contacts between the participants could be deepened which will lead to further progress.

Abstracts

Stable Polyhedra in Parameter Space

Jürgen Ackermann

(joint work with Dieter Kaesbauer)

Consider a polynomial family $P_i(s) = A_i(s)Q(s)+B_i(s)$, $i = 1, \dots , N$, all coefficients real. A_i and B_i given and $Q(jw) = R_Q+jI_Q$, I_Q fixed. Find the set of all simultaneous stabilizers R_Q for the polynomial family. For $i = 1$ it is shown, that the roots of $P_1(s)$ can cross the imaginary axis only it singular frequencies ω_k , $k = 1, \dots , K$, which are determined as roots of a polynomial in ω^2. Each singular frequency gives rise to a hyperplane in R_Q-space. The hyperplanes partition the R_Q-space into stable and instable polyhedra.

The simultaneous stabilizers for the polynomial family are found as intersection of the stable polyhedra for $i = 1, \dots , N$. A dual result holds for fixed R_Q in the I_Q-space. This suggests a design procedure for $Q(s)$ with alternating steps in the R_Q and I_Q spaces.

A control engineering application is the design of a robust PID controller that simultaneously stabilizes a plant family. Then $Q(s) = K_I + K_p s + K_D s^2$. For fixed K_p stable polygons in the (K_D, K_I)-plane are obtained. Rather than gridding K_p and factorizing for $\omega_K(K_p)$ it is easier to evaluate the inverse function $K_p(\omega)$. It shows the ranges of K_p, for which stable polygons in the (K_D, K_I)-plane (and how many of them) exist.

Feedback Invariants of Smooth Control Systems

Andrei Agrachew

Let M be a smooth manifold and $TM \to M$ be its tangent bundle. We treat a control system with the state space M as a submanifold U of TM. A curve $\gamma : [t, \tau] \to M$ is an admissible trajectory of the control system if its velocity at every point belongs to U. We study the *boundary mapping* $\gamma(\cdot) \mapsto (\gamma(t), \gamma(\tau))$ from the space of admissible curves into $M \times M$; not just combinatorial properties of this mapping like in algebraic topology but its geometric and analytic features. Critical points of the boundary mapping a called *extremal paths*. Special cases are: Riemannian geodesics (if U is the spherical bundle of a Riemannian structure) and characteristic curves of Pfaffian systems (if U is a linear subbundle). Curvature–type feedback in variants come from the analysis of the local structure of the set of extremal paths and their natural lifts to the cotangent bundle T^*M provided by the associated *Lagrange multipliers.*

A new approach to classical moment problems, with applications to control, systems and signals

Christopher I. Byrnes

Classical moment problems include several interpolation problems which have been important in systems and control and in signal processing. Nevanlinna-Pick interpolation by rational functions and the rational covariance extension problem are two examples, with the first interpolation problem having applications to robust control and to circuit theory and the second interpolation problem having applications to stochastic realization theory and to spectral estimation. In this talk, I will present joint work which solves these problems by solving a convex, nonlinear optimization problem which can be formulated as a solution method for the general classical moment problem.

Polynomial equations giving a proper feedback compensator for a strictly proper plant

Frank Callier

Our purpose is a review of the polynomial matrix compensator equation $X_l D_r + Y_l N_r = D_k$ (COMP), where a) the right-coprime polynomial matrix pair (N_r, D_r) is given by the strictly proper rational plant right matrix-fraction $P = N_r D_r^{-1}$, b) D_k is a given nonsingular stable closed-loop characteristic polynomial matrix, and c) (X_l, Y_l) is a polynomial matrix solution pair resulting possibly in a (stabilizing) rational compensator given by the left fraction $C = X_l^{-1} Y_l$. We recall first the class of all polynomial matrix pairs (X_l, Y_l) solving (COMP) and then single out those pairs which result in a *proper* rational compensator. An important role is hereby played by the assumptions that a) the plant denominator D_r is column-reduced, and b) the closed-loop characteristic matrix D_k is row-column-reduced (e.g. monically diagonally degree dominant). This allows to get all solution pairs (X_l, Y_l) giving a proper compensator with row-reduced denominator X_l having a priori prescribed (sufficiently large) row degrees.

Entropy for Perturbed Systems

Fritz Colonius

Topological entropy for dynamical systems is a standard tool to characterize complex behaviour. In this talk topological fibre entropy for ordinary differential systems with a class of time dependent for perturbations is considered and related to a version involving chains, in the chain recurrent set. Here local accessibity and an inner-pair condition relating orbits for different perturbation ranges, have to be assumed.

Robuste Regelung eines parameterabhängigen Übertragungssystems [Robust control of a parameter dependent plant]

Nicolas Dourdoumas

Die robuste Regelung parameterabhängiger Übertragungssysteme stellt große Anforderungen an das zu ermittelnde Regelgesetz. Wenn allerdings am Prozess die veränderlichen Parameter messtechnisch erfaßt werden können, so ist es sinnvoll, diese für den Entwurf eines parameterabhängigen Reglers zu verwenden. Mit solch einem Regelsatz können gegenüber einem parameterunabhängigen Regler wesentliche Verbesserungen erzielt werden. Dies wird gezeigt an einem neu entwickelten Labormodell, bei dem während des Betriebes (!) ein messbarer physikalischer Parameter **gezielt** verändert werden kann. Es wurde das entwickelte Modell näher erläutert, die Reglersynthese beschrieben und auf die Implementierung des linearen parameterabhängigen Regelgesetzes (LPV-Regelung) näher eingegangen. Bemerkenswert für die Effizienz des entwickelten Regelkonzeptes ist, dass obwohl vom mathematischen Standpunkt aus gravierende Vereinfachungen bei der Modellbildung gemacht wurden, sich erstaunlich gute Ergebnisse beim **realen** Ablauf zeigen.

Towards an algebraic setting for identification

Michel Fliess

In this joint work with H. Sira-Ramirez we propose a new method for calculating unknown coefficients of linear systems. These computation which are very fast can be made robust with respect to a large variety of perturbations. Several convincing simulations are presented.

Quasi–stationary Approximations and Slow Manifolds

Dietrich Flockerzi

Quasi–stationary and slow manifolds are often used in finite or infinite dimensional control systems with different scales to obtain a reduced ODE–model for which the control synthesis is much easier to handle. In chemical engineering and in combustion problems one encounters a reduction mechanism proposed by Maas & Pope which can only be justified for a restrictive class of systems. By means of examples we show that a so–called *Intrinsic Low–Dimensional Manifold*

- need not be an approximation of a slow invariant manifold,
- need not predict the true behaviour of the flow even if it is near an slow invariant manifold,
- need not possess the desired attractivity properties of a slow invariant manifold,
- need not be of the same dimension as a slow invariant manifold would be.

It is therefore a problem of great interest to single out the class of (chemical) systems for which the approach of Maas & Pope leads to useful reduced models.

Qualitative and quantitative aspects of the input–to–state stability property

Lars Grüne

In this talk we present results on the input–to–state stability (ISS) property for nonlinear perturbed systems. In the first part, we investigate the qualitative nature of this property. The main result is a theorem obtained together with E. Sontag and F. Wirth, which states that the ISS property is equivalent to the nonlinear H_∞ property under suitable nonlinear changes of coordinates.

In the second part we focus on quantitative aspects of ISS. We introduce a variant of ISS, called input–to–state dynamical stability (ISDS), which utilizes a 1d dynamical system in order to describe the decay both of large initial values and of past disturbances. Here the main result is that ISDS allows for a gain preserving Lyapunov function characterization which in particular allows to give estimates for the ISDS (and ISS) robustness gain. As an application we consider a quantitative version of a nonlinear small gain theorem.

Windup prevention for unstable systems

Peter Hippe

The majority of windup prevention schemes assumes a stable linear part (eigenvalues) in the open left half s-plane with simple eigenvalues on the imaginary axis allowed). Fortunately, most control applications meet this requirement, and in classical PID control loops, the only problems caused by the saturating plant input usually result from the integral action in the controller (the so-called *integral windup or controller windup*).

It fast closed loop dynamics have been assigned, control signal saturation can give rise to an oscillating behaviour or to limit cycles *plant windup* even for exponentially stable compensators. Whereas the controller windup can be removed by a multitude of measures [1], the plant windup has not been discussed so often. Known results (for stable systems) are e.g. the so-called additional network [2] or the approach presented by A. Teel [3].

However, both plant windup prevention measures are not applicable to exponentially unstable systems. There has been an attempt to handle the case of step-like reference inputs for such systems [4], but the presented scheme can be demonstrated to become unstable for arbitrary reference input changes. Obviously no windup prevention scheme is able to guarantee closed loop stability for arbitrary reference signal changes, if it becomes active only after the saturation limit has been hit for the first time.

A very important aspect in exponentially unstable systems with input saturation is the fact that there has to be an sufficient input signal reserve for disturbances rejection at any time. This also rules out schemes that only become active after the reference signal has caused the input signal to saturate.

Presented is a new windup prevention scheme allowing to assign the desired disturbance rejection properties, which usually entails severe plant windup effects, an to handle arbitrary reference signal changes within an amplitude range that is limited only by the saturation amplitude and by the necessary input amplitude reserve required for disturbance rejection.

This becomes possible by using a nonlinear trajectory planning for the reference signals in conjunction with a nominal (linear) control to achieve the desired disturbance rejection. The presented scheme works for unstable and stable systems alike and is easily tunable. A rather virulent unstable system with four exponentially unstable modes is used to demonstrate the design procedure.

References

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Geometrical Methods for Pole Assignment Algorithms

Knut Hüper

A differential geometry approach for the design of output feedback pole assignment compensators is presented. Continuing on earlier joint work with Uwe Helmke the output feedback control problem is formulated as a minimization problem on projective space. A thorough discussion of the critical point set of the objective function is done. A simple Jacobi-type algorithm is proposed to achieve minimization of the objective function. Several ideas are presented to accelerate convergence. We comment on structured systems as well as indicate how to solve the bigger class of matrix extension and inverse matrix eigenproblems numerically in an efficient way.

Tracking with pre-specified transient behaviour

Achim Ilchmann

We consider a class of nonlinear functional differential equations, encompassing linear minimum phase systems of relative degree one with positive high-frequency gain. A single time-varying proportional error feedback controller is introduced which guarantees that the norm of the error stays within a pre-specified "funnel".

Robust Tracking of Uncertain Trajectories

Alberto Isidori

This works illustrates the principles underlying the design of an autopilot able to secure smooth landing of the helicopter on a oscillating deck (such as the deck of a ship in rough seas) in uncertain conditions. The control objective is conveniently divided into two separate tasks: the first is the synchronization of the vertical motion of the helicopter with that of the deck at a given distance H. Once synchronization has been achieved, the second task is to provide a smooth landing, letting the vertical offset H decay to zero. Clearly, the crucial part is the design of a controller to accomplish the first task. The problem becomes quite challenging if the information available for feedback is provided by passive sensors only, yielding the relative position between the helicopter and the deck. If this is the case, the vertical reference trajectory to be tracked by the helicopter is not available, but must be estimated in real time by processing the synchronization error. Recent progresses in internal-model-based control and in nonlinear stabilization theory make it possible to achieve the desired design goal.

Disturbance attenuation: an alternative concept

Hans-Wilhelm Knobloch

The lecture concerns affine control systems

$$\dot{x} = p(x) + B(x)\,u + G(x)\,w\ ,\ y = h(x)$$

with total input u (=control), w (=exogeneous disturbance). y is the measured (and to-be-controlled) output. The problem is the design of control strategies. We discuss the following design objectives.

1. Stabilization of the state x in the presence of a bounded disturbance ($||w(t)|| \leq \omega_0$, ω_0 known). $y = V(x)$, we wish to keep V ultimately bounded along a given trajectory.
2. Identification of $w(t)$ from (inaccurately) measured output $y = V$.

Objective (2) is of particular interest from the viewpoint of applications. We propose a solution of (1) and (2) by discontinuous state feedback u. The t-axis is divided in subintervals $[t_i, t_{i+1}]$, $t_{i+1} - t_i = \delta$, δ small. u is then defined in each sampling interval as follows

$$u = P(x - x(t_i)) + u_i(\xi, \theta)\ ,\ \theta := \frac{1}{\delta}(t - t_i)\ ,\ t_i \leq t < t_{i+1}$$

ξ a parameter, with $\xi \gg 1$. The main contribution of the lecture is a construction of $u_i(\xi, \theta)$ which allows a (short-time-mean-value)- reconstruction of w from a formula of this type

$$\frac{1}{\delta}\left(V(x(t_i + \delta)) - V(x(t_i))\right) = V_x B \int_{\frac{1}{2}}^{1} u(1, \theta) d\theta + p + \xi^2 V_x G \frac{1}{\delta} \int_{t_0}^{t_0 + \delta} w(t) dt + O(\delta)$$

where $O(\delta)$ does not depend upon ξ.

Nonlinear observers for autonomous Lipschitz continuous systems

Gerhard Kreisselmeier
(joint work with Robert Engel)

For autonomous systems $\Sigma : \dot{x} = f(x), y = h(x)$, where $f : \mathbb{R}^n \to \mathbb{R}^n$, $h : \mathbb{R}^n \to \mathbb{R}$ are Lipschitz continuous, we consider the problem to recover the present state x from past measurements of the output y. Under the hypothesis that Σ is observable and of finite complexity, it is shown that a suitable observer exists and can be obtained as $\dot{z} = Fz + gy$, $\hat{x} = Q(z)$, $z \in \mathbb{R}^m$, i.e. as a linear filter followed by a nonlinearity.

The Design of Observers for Nonlinear System

Arthur J. Krener

We give a survey of some of the many ways of designing an observer for a nonlinear system. The simplest method is observers via linear approximation about a reference point or reference trajectory. We then discuss observers via linearization of the error dynamics in transformed coordinates. We review the older method which requires that a restrictive set of integrability conditions are satisfied and the newer method which depends on non resonance conditions which are almost always satisfied. Recently Krener and Xico have extended the letter and shown their every real analytic system that is linearly observable admits a local observer with linear error dynamics in transformed coordinates. This suggest the question: What are the obstructions to global error linearization. We then discuss high gain observers and their poor performances in the presence of noise. The observer of Krener and Kang is presented. We then turn to various infinite dimensional observers; the nonlinear filter, the minimum energy estimation and the H^∞ estimation. Finally we discuss the use of multiple extended Kalman filters which we believe is the best current general purpose method.

Reachability and the Target Problem

Alexander B. Kurzhanski

The presentation deals with the target control problem under unknown but bounded disturbances or state constraints, when one is to verify whether a controlled system reaches a given target for all controls or for some control (at some time or at given time),or totally avoids it. The solution is based on solving the problem of forward or backward reachability under uncertainty and/or state constraint. The problem is more complicated when the target set is in itself a reachability tube for another system. In the latter case one has to investigate HHB or HJBI equations generated by dynamic optimization problems with nonintegral functionals (like the Chebyshev functional or similar, but nonconvex functionals).

For systems with original linear structure the solution may be based on an ellipsoidal calculus that gives external and internal approximations of the respective reach sets and thus allows effective approximation of the solution to the target problem.

The design of mechatronic systems and the generalized cascade principle, exemplified at the test-shuttle of the "Neue Bahntechnik, Paderborn"

Joachim Lückel

The realisation of complex mechatronic systems shows a long way from the theoretical preparation, the modelling, the controls design and implementation, producing the test element and preparing the tests. By the way the complexity of the systems is one of the biggest problems, with many subsystems, different physical effects and many degrees of freedom. Therefore it is necessary, to organize the system, e.g. in a modularized/linear manner. At the MLap we use since some years an approach, which is adapted to the concept of engineers of aggregate. We use, from the lowest level, Mechatronic function modules (MFM), autonomous mechatronic modules (AMF), cross linked mechatronic modules (CMS). We propose now, to generalize the classical method of cascaded controller design to this system and combine it with the mixed usage of SISO/MIMO-methods. As an example we show the design, layout and tests of the suspension/tilt-module of the test shuttle of the "Neue Bahntechnik, Paderborn".

Representation of quantised systems by the Frobenius-Perron operator

Jan Lunze

The paper concerns continuous-variable discrete-time systems with quantised input and state. It shows that the autonomous quantised system is represented by the Frobenius-Perron operator and the non-autonomous system by the Foias operator. A finite and complete approximation of the Frobenius-Perron operator is given by an automaton which turns out to be identical to the discrete abstraction of the quantised system that is currently studied in the literature on verification of logic control algorithms or the diagnosis of hybrid systems. Hence, the paper shows a connection between the mathematical literature and hybrid systems research. As a result of this connection, it is shown that the abstraction converges to the continuous system for finer quantisation. Furthermore, the paper presents a method for the computation of abstractions that guarantees the completeness of the resulting model.

Robust stability of time-varying systems with the Lyapunov method

Mohamed Mansour

This work considers the robust stability of time varying linear systems described by a linear differential equation whose coefficients vary inside given intervals and with restricted magnitudes of the rates of change of the coefficients. This problem can be considered as a generalization of the Kharitonov problem, which is in turn a generalization of the Hurwitz problem and it was formulated as an open problem by the author in 1992. To solve this problem Lyapunov theory is used where a Lyapunov function is obtained which is multi-affine in the polynomial coefficients using characteristics of positive real functions and Kalman-Jakobowich- Popov lemma. With this Lyapunov function extreme point results are obtained. The structure of the Lyapunov matrix as well as the structure of the conditions for the solution of a robust positive real function problem are characterized. A second approach based on the critical stability conditions is also suggested but the Lyapunov matrix thus obtained is no longer in general multi-affine in the parameters. Examples of low order systems are given. The resulting stability conditions are only sufficient. An open problem for second order discrete system is formulated. This work was investigated together with Brian D.O. Anderson.

Delay systems and Nehari extensions

Gerrit Meinsma

There are two 'competing' approaches to H_∞ control for systems with delays. On frequency domain solution where the delay is separated from the J-spectral factorization problem using FIR-systems, and one where the delay is absorbed into the controller and only at a final step it is recognized that the controller must have the form $e^{-sh}K_n$. The second approach is easier to grasp and only at the final step does one have to solve a 'complicated' Nehari extension problem where the given bit is FIR. In the talk I show that the 'first' frequency domain approach is useful at this final stage of the second approach. Using the domain techniques we solve the Nehani-suboptimal extension problem for FIR systems of the type $h(t) = e^{At}B1_{[0,h]}(t)$, and thereby finishing the 'second' approach.

Optimal control of descriptor systems

Peter C. Müller

In recent years the analysis and design of control systems in descriptor form have been established. But still problems of optimal control design are open. The contribution deals with the generalization of Pontryagin's maximum principle for descriptor systems. Here, proper and non-proper behaviour of the dynamical systems plays an important role. Properness and non- properness distinguish the cases whether the descriptor systems are exclusively governed by the control inputs or their higher order time derivatives additionally. In the latter case a quite different problem of optimal design has to be considered. In both cases necessary conditions for optimal control are discussed.

Synchronization in a network of identical systems

Henk Nijmejer

In the talk a review is given of ongoing work regarding the asymptotic synchronization of a network of coupled identical systems. It is shown that, under appropriate conditions complete synchronization is achieved for sufficiently strong coupling. Interesting enough is that also intermediate cases can be studied with appropriate control techniques. Most notably, partial synchronization, i.e. synchronization of subset(s) of the network, can be described in terms of symmetries in the coupling structure and inside the systems.

A unified linear algebraic state model of electromechanical conversion (generator/motor) for general asymmetric electromechanical power conversion

Hassan Nour Eldin

The space vector state model for the electro-mechanical power conversion represents the flux as a rotating space vector that points to the maximum point of an assumed sinusoidal flux. A complex unit is used to represent this rotating space vector. A complete symmetric electro-mechanical conversion is assumed, with the result that it can not be applied for electrical power generators (assymmetric). It remained applicable only for symmetric motors. For not symmetric motors (permanent magnet), the use of the model leads to a nonlinear flux reactance which is dependent on the position angle of the state current space vector. By introducing the space hyper-complex to represent the spatial directions, it is shown that electrical power (active power/reactive power) is a space quaternion. The electro-mechanical power conversion model reduces to linear algebraic impedance with a complex unit z representing the axis of mechanical conversion, a time reactance, a resistance and a space reactance of the e.m. power conversion. The algebraic model has matrices with real positive coefficients, which are multiplied with the Clifford projectors (double numbers). The model is bi-directional, so that interchanging the input/output and the direction of rotation leads the e.m. conversion to change from generator to motor. The model clearly shows that asymmetrical e.m. converters cannot perform as pure generator or motor. A dynamic coupling between the generator and motor dynamics exist (generator as well as motor). Only symmetrical e.m. power conversion decouple.

Bicycle routing for maximum suntan

Geert Jan Olsder

A cyclist starts cycling from his house at sunrise, cycles throughout the day at a constant, positive, speed in such a way that he returns home at sunset. He is free to choose the direction in which he cycles. It is assumed that the countryside in which he cycles is a plane without obstacles such as trees or ditches. Put on other words, the cyclist can choose any direction he wishes. The only hard conditions are that he return home exactly at sunset and that the speed be given and constant. This optimal control problem is solved with both the maximum principle and the calculus of variations. The adjoint variables in the maximum principal approach (which happen to be constant) are integration constants when solving via the Euler equations. In the analysis one encounters elliptic integrals of first and second kind. Several slightly different variations on the theme are treated, with some surprising phenomena.

Aspects of repetitive and iterative learning control

David H. Owens

The paper renewed the ideas of iterative learning control (ILC) motivated by repetitive operation of robots and the use of repetitions to improve tracking accuracy. The problem of control design is the creation of a stable iterative control operation which naturally takes the form of an optimization problem. Here qualitative control approaches were included and the effects of non-minimum-phase plant characteristics on convergence rate summarized. Predictive Optimal ILC was seen to solve the problem at the expense of 'impulsive' control actions. Given the value of optimization as the core of control design for ILC, the performance of very simple optimal ILC was indicated using parameter optimal ILC. Convergence is achieved under specific system conditions and geometric convergence achieved using an 'adaptive' objecture function approach. Work continues!

Analysis of interconnected systems using density functions

Anders Rantzer

In this presentation we, compare the properties of Lyapunov functions and the recently introduced concept of "density functions". It is noted that Lyapunov functions have very attractive properties in the analysis of interconnected systems. This is expressed in passivity theorems and gain analysis. Corresponding properties are not available for density functions. On the other hand, density functions enjoy a very attractive convexity property in control synthesis, which does not hold for Lyapunov functions. Given this background, we discuss the possibilities to combine the two concepts for synthesis of stable interconnections. In particular, a framework of stochastic systems is discussed.

Distance to observability, Riccati equations and observers for nonlinear systems

Gauthier Sallet

We give a very simple algorithm to compute the distance $\delta(A, C)$ of a observable pair (A, C) to the nearest pair with an unobservable imaginary mode. This algorithm gives rise to a new algorithm to compute the distance to undetectability (respectively) to unobservability for a pair (A, C).
It turns out that the first quantity δ is useful to design an asymptotic observer for systems

$$(1) \qquad \begin{cases} \dot{x} &= Ax + \Phi(x, u) \\ y &= Cx \end{cases}$$

Where $\Phi(x, u)$ is globally Lipschitz with respect to the state $x \in R^n$, uniformly in the control $u \in R^p$, i.e. there exists a constant γ such that

$$(2) \qquad \|\Phi(x, u) - \Phi(y, u)\|_2 \leq \gamma \|x - y\|_2$$

for all (x, y) and all u.
and the pair(C, A) is observable.
We propose also a robustness result for stabilisation of uncertain systems related to this quantity δ. Relation with classical literature is explored. It turns out that the quantity δ is the distance of (C, A) to undetectability.

Time-optimal controls for bilinear (chained) systems

Andrej V. Sarychev

In our earlier work (with H. Nijmeijer) we managed to describe completely of extremals (normal, singular and abnormal ones) for a class of 2 chained systems. While time- optimality of abnormal and singular extremals can easily be checked, optimality vs non-optimality of the bang-bang normal extremal remained an open question. In our talk we represent results on time-optimality for bang-bang extremals for chained systems in dimensions n = 3 and n = 4. The latter case is related with sub-Riemannian problem for the Engel structure.

On the design of structured controllers

Carsten W. Scherer

For the parallel interconnection of multiple individually controlled systems we discuss how to solve the corresponding decentralized controller synthesis problem by convex optimization. In our main contribution we develop, under a specific one-block hypothesis on just one subsystem, a semi-definite programming algorithm that allows to design controllers for optimal H_1-attenuation whose McMillan degree is bounded in terms of the underlying plant description. The relevance of the new algorithm is substantiated by revealing the close interplay with multi-objective control, and by showing applications to controller synthesis for chained systems and for systems that are affected by uncertain stochastic noise.

Lie-group-analysis for nonlinear implicit systems

Kurt Schlacher

This contribution presents methods for the control of nonlinear implicit dynamics systems. It is shown that non accessible or non observable systems admit symmetry-groups acting on their solutions such that distinguished parts of the system remain unchanged. The approach uses the geometric picture that a dynamic systems is represented by a submanifold in a suitable jet-space. It reproduces all results well known for explicit control systems but is straightforward applicable to the implicit case, if these systems are formally integrable. The proposed Lie group approach joins different types of definitions for accessibility and observability, since this Lie groups act on the solutions of the system and their existence depends on the systems equations only. It is worth mentioning that Lie groups might be the right tool to treat the accessibility and observability problems for sampled data and infinite dimensional systems.

Vibrational Control of Singularly Perturbed Systems

Klaus R. Schneider

We consider autonomous singularly perturbed systems and assume that there exists an unstable equilibrium. The goal is to stabilize that equilibrium by generating an asymptotically stable periodic solution near the unstable equilibrium. To this purpose, we apply an oscillating force with high frequency and low amplitude. By means of the persistence of normally hyperbolic invariant manifolds, the averaging theory and appropriate transformations we establish results on the vibrational and partially vibrational stabilizability of the equilibrium under consideration.

Computation of optimal switching times

Rodolphe Sepulchre

Consider the standard time-optimal control problem for single input linear controllable systems in dimensions n. The time-optimal solution is bang-bang and involves at most $n-1$ switchings provided that the optimal time is bounded by $\frac{\pi}{\omega}$, where ω denotes the maximal imaginary part of the spectrum of the system matrix. The computation of the time-optimal control then reduces to the computation of n time-intervals between consecutive switchings

$$x_1 = t_1 - t_0 \ , \ x_2 = t_2 - t_1 \ , \dots , \ x_n = T - t_n \ .$$

Under these assumptions, we construct and provide a convergence analysis of a continuous-time flow that "computes" the optimal sequence. This algorithm is a continuous-time and singularly perturbed version of a discrete algorithm proposed by Yatzeboff (1969) without convergence analysis.

High-order and non-smooth necessary conditions for an optimum in a unified framework

Hector J. Sussmann

We present a general axiomatic definition of the notion of a "generalized differentiation theory," which is a way to assign to certain set-valued maps between finite-dimensional spaces, at certain points, a set-valued derivative which is a nonempty compact set of linear maps rather a single linear map. The properties required by the axioms are, simply, the chain rule, the Cartesian product rule, locality, and invariance under continuously differentiable diffeomorphisms. Examples of such theories other than the classical differential are: J. Warga's "derivate containers," two differentiation theories introduced by H. Halkin, and some others recently proposed by us, such as the "multi-differentials" and the "generalized differential quotients." In the lecture, we introduce still another theory, of the so-called "path-integral generalized differentials," which has the desirable feature of containing all the other theories.

New relaxations for parametrized and robust LMI Problems

Bernd Tibken

In this talk the notions of robust and parametrized LMI's are introduced and it is shown that there are only a few approaches to tackle robust LMI's. The problem of checking asymptotic stability of an interval matrix is used as an instructive example. In this case the number of vertex matrices to be checked for negative definiteness of $A^T P + PA$, where A is an interval matrix and P is positive definite is 2^{n^2}. In this talk it is shown how new results from real algebraic geometry, namely, the representation theorem of Jacobi and Prestel can be utilized in order to compute a relaxation. In this context relaxation means that a sufficient set of ordinary LMI's is generated. For the structured problem of an interval-matrix it is shown how this relaxation together with a generalized eigenvalue optimizer leads to robustness bound which are less conservative than the previously known.

Interconnections, regular implementability and singular feedback

Harry L. Trentelmann

In this talk we will discuss the issue of control as interconnection in a behavioural framework. Suppose we have a plant with two types of variables. On the one hand, we have variables whose trajectories we intend to shape (called the *to-be-controlled variables*), denoted by w, while on the other hand we have variables over which we can attach a controller (called the *control variables*), denoted by c. A controller is a linear differential system with manifest variable c. The w trajectories that remain possible after restricting the plant's control variable c to be an element of the controller behaviour, form the manifest controlled plant behaviour. Recently [1], [2], a characterization has been given of all linear differential behaviours that can be obtained as manifest controlled plant behaviour by interconnecting the given plant with a suitable controller. More recently, a characterization has been given of all behaviours that can be obtained in this wy by *regular interconnection through c*. In this talk we will discuss these results. We will also show that every regularly implementable behaviour can in fact be implemented by singular feedback, thus generalizing, earlier result from [4] on the case of full interconnection. Finally, we will discuss the application on these results to the problems of pole placement, stabilization and synthesis of dissipative systems.

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Dissipative distributed systems

Jan C. Willems

I considered systems described by linear constant coefficient PDE's. A system is said to be dissipative if a given quadratic differential form integrated over time and space is nonnegative. I proved that this is equivalent to the existence of a storage function and a flux such that the rate of change of the storage plus the flux does not exceed the supply rate. This existence is a consequence of Hilbert's 17-th problem on the factorization of rational functions in many variables.

Zubov's Method with Inputs

Fabian Wirth
(joint work with Fabio Camilli, Lars Grüne)

We consider ordinary differential equations in $\mathbb{R}^n$ of the form

$$\dot{x} = f(x)\,,$$

assuming standard Lipschitz conditions. Let $x^* = 0$ be an asymptotically stable fixed point and define the domain of attraction to be the set of initial conditions that converge to 0 under the flow. Zubov's theorem asserts that for an asymptotically stable fixed point of an ordinary differential equation a maximal Lyapunov function (i.e. one that works on the whole domain of attraction) can be found via the solution of the first order PDE

$$Dv(x) \cdot f(x) = -h(x)(1 - v(x))\sqrt{1 + \|f(x)\|^2}\,,$$

where h is some nonnegative auxiliary function vanishing only at $x = 0$. In particular, the solution v characterizes the domain of attraction as $v(x) \in [0, 1)$ is equivalent to the statement that x is in the domain of attraction.

We discuss how this result can be extended to perturbed systems, that is systems of the form

$$\dot{x}(t) = f(x(t), d(t))\,,$$

where the functions d are measurable taking values in some compact subset of $\mathbb{R}^m$. Assume that 0 is a fixed point for all perturbation values d and that it is locally asymptotically stable uniformly with respect to all solutions of the system. We then define the *robust domain of attraction* to be the set of all points that converge to the origin under the flow, for all time-varying perturbations in our class.

It can be shown that the solutions of the following straightforward generalization of Zubov's equation characterize the robust domain of attraction just as in the classical case.

$$\begin{cases} \inf_{d \in D} \{-Dv(x)f(x,d) - (1 - v(x))g(x,d)\} = 0 \\ v(0) = 0 \end{cases}$$

The approach is based on a reformulation of the problem as an optimal control problem and on the consideration of the associated value functions. These are solutions in the viscosity sense of the above equation.

Under mild conditions on the auxiliary function g it can be ensured that the solution v is locally Lipschitz. A regularization scheme that removes the singularity of Zubov's equation at 0 is available.

Nonlinear observer design under reduced observability properties

MICHAEL ZEITZ

Considered are smooth nonlinear single input single output systems of order n, $\dot{x} = f(x, u), y = h(x)$, whose Taylor linearization at some operating points is not observable, and smooth observer design is not possible. The reduced observability properties are defined by means of the r-observability map q_r, which relates the state x with the output y and $r - 1$ of its time derivatives. The length $r \geq n$ is chosen such that q_r is injective and an inverse map $q_r^I : R^r \to R^n$ exists. Using the map q_r as coordinate transformation, the input dependent r-observability form is obtained, where the dynamic description of the system is lumped in a single nonlinear function φ. The properties of q_r, q_r^I, and φ define the following reduced observer design strategies:

(i) For q_r^I continuous and not smooth, the properties of φ determine the observer design. When φ is Lipschitz continuous, a continuous observer [1] can be designed by an arbitrary method. When φ is not Lipschitz, an approximate high gain observer design [2] is proposed.

(ii) If injectivity of q_r is lost for bad input points $u(t_i^*)$, the design of an event-based observer [3] is possible, when the system trajectories cross these bad input points t_i^* fast enough, i.e. under input restrictions.

(iii) For $r > n$, a further reduction of observabilty happens and an expanded order r-observability form defined on an n-dimensional subset in R^r is needed. Thereby, the degrees of freedom for the construction of q_r^I can be used such that the φ-function is smooth or Lipschitz [4]. Otherwise, an approximate or event-based observer of expanded order must be designed.

The cases (i) - (iii) are illustrated using some examples and a batch bio-reactor model. - The presented results are based on the sandwich PhD work of Alejandro Vargas from Mexico under the supervision of Dr. Jaime Moreno and the author.

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Abstracts of the open problems in mathematical systems and control theory

The abstracts for the open problems presented by Hector Sussmann and Anders Rantzer have been included into the corresponding abstracts of their talks given during the other sessions of the workshop. Therefore, the abstracts have not been repeated here.

The gap between *A is the generator of a bounded semigroup $T(t) := exp(At)$* and *A is similar to the generator of a contraction semigroup*

Frank Callier

It is well-known that a linear closed densely defined operator A on a Hilbert space H generates a bounded semigroup if it is similar to the generator of a contraction semigroup. Is it possible that if A generates a bounded semigroup, then it is similar to the generator of a contraction semigroup? The literature is apparently silent on this question.

Rate preserving control Lyapunov functions

Lars Grüne

Motivated by recent results on perturbed nonlinear systems [1,2] we pose the following question:
Given a nonlinear control system which is asymptotically controllable with a prescribed decay rate, is it always possible to find a continuous control Lyapunov function which represents this rate?

Note that continuity of the control Lyapunov function is important in this question, since it follows as a special case from Theorems 4.5.4 and 4.5.5 from [1] that a discontinuous control Lyapunov function does always exist.

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The state partitioning problem

Jan Lunze

The problem concerns quantised systems whose output y can only be measured through a quantiser that generates the quantised output $[y]$ and whose discrete input $[u]$ is transformed into a real-valued input u by an injector. As any control equipment has only access to the quantised signals $[u]$ and $[y]$ rather than to the real-valued signals u or y, respectively, the quantised system is a system with discrete input sequence

$$[U(0...k)] = ([u(0)], [u(1)], \dots , [u(k)])$$

and discrete output sequence

$$[Y(0...k)] = ([y(0)], [y(1)], \dots , [y(k)]).$$

The quantiser and the injector induce partitions of the input and the output space of the system. An input event symbolises a change of the input and implies that the real-valued input u lies on the hypersurface between adjacent input space partitions. Likewise, an output event does not describe the real-valued output y precisely, but gives only the information that the real-valued output lies on the hypersurface of two adjacent output space partitions. The ambiguity of the description of the system behaviour by event sequences implies, in general, that the output sequence $[Y(0...k)]$ cannot be unambiguously determined for a given input sequence $[U(0...k)]$. Hence, the quantised system is nondeterministic.

The problem asks for input and output space partitions under which the discrete-event behaviour of the quantised system becomes deterministic.

State and first order representations

JAN C. WILLEMS

Let B be the set of distributional solutions of a system of linear constant coefficient partial differential equations. Let $S_-, S_+ \subseteq \mathbb{R}^n$ (:= the set of independent variables) be non-overlapping open sets. Define $S_0 := \mathbb{R}^n - (S_- \cup S_+)$. Call B Markovian if $w_1, w_2 \in \mathrm{B} \cap C^\infty$ and $w_1 |_{S_0} = w_2 |_{S_0}$ imply $w_1 \wedge_{S_0} w_2 \in \mathrm{B}$, where $w_1 \wedge_{S_0} w_2$ is defined by $w_1 \wedge_{S_0} w_2 |_{S_-} = w_1 |_{S_-}$ and $w_1 \wedge_{S_0} w_2 |_{S_+} = w_2 |_{S_+}$. Conjecture: B is Markovian if and only if B is the solution set of a system of first order linear constant coefficient partial differential equations.

Edited by Bernd Tibken

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