MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 12/1999

Regelungstheorie

21.03.-27.03.1999

This meeting was organized by H. Kwakernaak (Enschede) and M. Thoma (Hannover). The considerable international interest is demonstrated by the great number of 40 participants coming from Germany, the Netherlands, United Kingdom, Russia, France, USA, Austria and Czech Republic. Like in previous events, the given lectures and numerous critical discussions between the participants have improved the dialogue and the scientific exchange between mathematicians and engineers. This interdisciplinary cooperation is unique to the meetings 'Regelungstheorie'. The altogether 35 talks focussed on mathematical problems from control theory to applications involving a wide spectrum of mathematical disciplines. Nonlinear systems again represented a main topic followed by event-driven or hybrid systems, robust stability and observers.

F. Allgöwer posed the question: How nonlinear is nonlinear and presented a measure for the nonlinearity of a system which is computed by comparing the system with its most accurate linear approximation. Several participants addressed the problem of stability. The robust stabilization of nonlinear systems by output feedback was the subject of A. Isidori's talk. He presented a new approach which takes advantage of the terms which connect the zero dynamics to the equation in which the control enters explicitly. F. Colonius proposed a generalization of the stability radius of linear differential equations subject to perturbations to nonlinear differential equations. The robust stability of time-varying system was addressed in two talks. M. Mansour solved the Kharitonov robust stability problem for time-varying continuous and discrete-time linear systems whereas A. Ilchmann considered linear systems which are controlled using a gain scheduling scheme. Changing the control parameter leads to time-varying systems for which the existence of stability radii were proved. Stability results for infinite-dimensional linear systems subject to low-gain integral control and static actuator nonlinearities were derived by H. Logemann. The problem of exchange of stabilities was addressed by K. R. Schneider. In the case of dynamic bifurcation, a delayed exchange of stabilities can cause fast transition which should be avoided. Methods to stabilize fixed points of discrete control systems were introduced in the talk. K. Schlacher presented methods for the geometric control of nonlinear descriptor systems described by implicit differential equations. By transforming an implicit system to an intermediate one which resembles an explicit control system as much as possible, well known analysis techniques can be applied to the system. W. Respondek focussed on non-holonomic control systems described by Goursat structures. The aim of the talk was to describe singularities for which Goursat structures are not equivalent to Goursat normal forms where well-known control techniques fail to work. The restoration of signals along an electric line described by the telegraph equation was presented by M. Fliess. The distortion of the signal along the line is compensated. The proposed control synthesis exploits operational calculus and aspects of module theory.

Several talks were dedicated to event-driven or hybrid systems. J. Lunze considered continuous-time systems whose state is quantised. The only measurements of the system are the transitions of the state from one quantity to another which is called an event. The problem of finding a model which gives the event sequence if the initial event is given was solved by the representation of the systems by semi-Markov processes. Methods to transform so-called switched continuous systems to Timed Automata respectively Rectangular Automata in order to be able to apply verification techniques known from computer sciences to the design of event-driven controllers were presented by O. Stursberg. The verification is then based on the reachability analysis, i.e. it has to be shown that forbidden system states can not be reached. D. Franke addressed the problem of robust stability of hybrid feedback systems in the presence of uncertain parameters. A two dimensional approach is presented where the time and the event counter are considered as independent variables. In the case of sampling, this approach leads to a three dimensional interpretation. A method for modeling constrained linear systems, some discrete-event systems or piecewise linear systems was presented by M. Morari. For these so-called Mixed Logical Dynamical Systems which are of considerable practical importance, several control design techniques were derived. G. J. Olsder uses the max-plus algebra for the synchronization of traffic lights in order to optimize green waves. Eigenvalues and eigenvectors in the max-plus algebra turned out to be of great importance for the solution of this problem.

Since observers play an important role in control systems, several talks focussed on this topic. A. J. Krener first introduced the notions of an observer in a 'narrow sense' (a dynamical system of the same order as the system that has to be observed) and in a 'broader sense' (a dynamical system of different dimension than the original system). He then presented a new back-stepping approach for the design of narrow sense observers which can be generalized to broader sense observers for a large class of systems. A design procedure for distributed parameter observer was derived by M. Zeitz. The observer correction can be injected both into the partial differential equation and into the boundary conditions. Some practical examples were given. P. C. Müller addressed the problem of estimating nonlinear effects of a dynamical system by linear state observers. Although this approach leads to satisfactory results in practice, there are still open problems in the mathematical proof. As a new approach to linear observer design, U. Helmke presented the equivalence of minimal order observer problems for linear functionals with tangential partial realization problems. H. Nijmeijer considered communication using a chaotic transmitter system to mask the signal. Parameter identification methods are then used for the reconstruction of the signal. As a new result for sampled linear systems, G. Kreisselmeier proposed a new non-equidistant sampling scheme which guarantees preservation of observability and controllability under sampling.

H. W. Knobloch considered control systems influenced by exogenous disturbances. He proposed a control such that a dissipation inequality without discretization error is rendered valid. D. Flockerzi presented a game theoretic approach to nonlinear H_∞ problems. He connected solutions of the Hamilton-Jacobi PDE to integral manifolds of the related Hamiltonian ODEs. Suboptimal feedback strategies are then derived via boundary-value-problems and Riccati equations. G. Meinsma focussed on the inverse optimal control problem: Is a given controller optimal? If a well working controller can not be generated by an optimization method, this method is of limited use. He compared H_2- and H_∞-norm optimality and concluded that H_2 is in some sense better than H_∞. H. Kwakernaak presented very effective algorithms for H_∞ problems for descriptor systems. The key to the solution is given by a transformation of matrix pencils to the Clements form. New results on numerical algorithms for polynomial matrices were also presented by M. Šebek. The systematic use of Sylvester matrices and of Fast Fourier Transform leads to effective algorithms which were impressively demonstrated on-line. The complete modal synthesis for feedback design is well known in the time domain. P. Hippe derived a method for complete modal analysis in the frequency domain. The method makes use of so-called Pole Directions, i.e. characteristic vectors of the polynomial matrix which parametrizes the state feedback.

A. B. Kurzhanski addressed the problem of reachability of linear systems. It turned out that the calculation of reach sets is related to HJB- and HJBI-equations. H. Sussmanns talk was about a recent version of the well known maximum principle: It was formulated in terms of flows which are differentiable in a generalized sense. This general version can be applied to hybrid problems and systems with discontinuities, e.g. the very old problems reflection, refraction and the brachystrochrone. E. Zerz generalized the notion of strict system equivalence, which describes the relation between all least order realizations of a transfer matrix, to multidimensional systems. R. Ortega pointed out that modelling should become more important and that the tools have to be chosen for the applications, not vice versa. He presented some benchmark example from power systems and drives, in particular a switched controller for induction motors, in order to develop a performance-oriented theory for nonlinear systems with constraints. H. Nour Eldin discussed the complex state vector theory of Kovács for modelling AC drives. As an extension, a novel two-axis-model for the synchronous generator, which also can be applied to unsymmetrical machines, is derived. Thermal noise in nonlinear electrical networks that can not be represented by external noise sources was considered by W. Mathis. He derived a systematic approximation for thermal noise in reciprocal networks. The control system presented by J. Ackermann helps to reduce the weight of an Airbus airplane. The maximal load of the vertical tail-plane is determined by the engine out fault and the panic reaction of the pilot and can considerably be reduced by the proposed control. A new triplanar machine for precise processing and measurement tasks was considered by J. Lückel. He pointed out that for machines like this a new mechatronics design method is necessary. In contrast to the conventional geometric design, the overall system dynamic behaviour is then considered.

This year's meeting was the last organized by M. Thoma. He already participated at the first meeting in 1969 and was organizer since the third one. He helped to establish the meeting with his excellent experience and overview concerning the ongoing research in mathematics and engineering sciences. He always co-organized the meetings in a perfect, warm way and thereby gave rise to the very good, human atmosphere and the high scientific standard. We thank Prof. Thoma in the name of all participants.

Abstracts in alphabetical order

J. ACKERMANN

Robust control for engine out

Consider the vertical tailplane of an Airbus A340-600 airplane. Its maximal load (and therefore weight) is determined by the worst case scenario of an engine out failure in combination with a pilot panic reaction. The pilot reaction is caused by the fast growing yaw rate and typically occurs after 2 seconds.

In this talk a control system is proposed that reacts much faster to the yaw rate, keeps it smaller and thereby avoids the pilot panic reaction. The weight saving in the vertical tailplane is more than 100kg. The effect has been verified in the detailed Airbus simulation model, that is also used for certification.

F. ALLGÖWER

System structure assessment: How nonlinear is nonlinear?

By definition, a system is called nonlinear, if it is not linear. In many cases it is however not only of interest whether or not a system is nonlinear, but also the degree of nonlinearity is important. Nonlinearity measures can give an answer to this question and allow to quantify the "severeness" of nonlinearity of dynamic systems.

This presentation is concerned with the philosophy, definition, computation, and application of nonlinearity measures to the analysis and synthesis of nonlinear control systems. With a number of examples the usefulness of this concept for control system analysis will be demonstrated. Recent advances in the field of nonlinearity measures, that allow to treat significantly larger classes of nonlinear systems, will be discussed. Furthermore a generalization of this concept to so-called suitability measures will be introduced and its usefulness for nonlinear system structure identification will be demonstrated.

F. COLONIUS

A stability radius for nonlinear systems

The stability radius of linear differential equations gives a measure for the robustness with respect to perturbations (which may be real or complex, constant or dynamic). A generalization for asymptotically stable equilibria of nonlinear differential equations which are subject to (real) time dependent perturbations is proposed and analyzed. It specifies the supremal range of the perturbations for which the control set containing the equilibrium is invariant. It is shown that this loss of invariance occurs when the invariant control set approaches to boundary of its invariant domain of attraction. Then it merges with a variant control set and itself becomes variant.

M. FLIESS

Controlling the telegraph equation and active restoration of some signals

In this joint work with P. Martin, N. Petit and P. Rouchon, we are compensating the distortion of an input signal along an electric line, which is modeled by the telegraph equation. This control synthesis, which is motivated by several simulations, continues some precious works on the wave, the heat and the Euler-Bernoulli equations. It also employs operational calculus and the algebraic interpretation of controllability obtained thanks to module theory. It extends to infinite dimensional systems the motion planning of flat nonlinear systems.

D. FLOCKERZI

Dissipation inequalities in nonlinear H_∞-theory

First we recall some aspects of dissipation inequalities for affine control systems with uncertain dynamics in a local set-up. In the second part we consider the game theoretic approach to the solution of a more general nonlocal nonlinear H_∞ scenario. we relate solutions of the Hamilton-Jacobi PDE to Lagrangian integral manifolds of the associated Hamiltonian ODEs. Thereby the computation of suboptimal feedback strategies can be done via 2-point BVPs in connection with time-variant Riccati equations. Finally we address alternative approaches where one is willing to accept certain restrictions on the acting disturbances.

D. FRANKE

On robust set stability of hybrid feedback systems

Mixed continuous-time and discrete-event systems are addressed, with a background in resource to task allocation processes. From a system theoretic point of view the hybrid feedback structure poses a problem of robust set stability in presence of uncertain plant parameters. A 2D-approach to stability analysis is proposed where continuous time t and counter of events k are formally independent variables.

In case of discrete-time sampling of the continuous subsystems control action can no longer be synchronized with process events. In a 3D-interpretation it will be shown that a solution to the overall problem ceases to exist if the sampling period exceeds a crucial upper bound. The approach will be illustrated at a hybrid thermal process.

U. HELMKE

Geometric control theory – revisited

This is joint work with P. A. Fuhrmann from the Ben Gurion University, Beer Sheva. Taking up an old theme of linear systems theory, i.e. geometric control theory a la Wonham, we report on a new approach to observer design of linear systems. It is shown that every conditioned invariant subspace has a kernel representation, as the kernel of a partial reachability matrix of some controllable pair. This then leads to a quick and clean proof of the equivalence of the minimal order observer problem for linear functionals with so-called tangential partial realization problems (this in turn is equivalent to tangential interpolation). We believe that the approach allows a better understanding of observer theory; in particular to the clarification of the role of almost invariant subspaces to high gain observer problems.

P. HIPPE

Complete Modal Synthesis in the frequency domain

Complete Modal Synthesis, also known as Parametric (state feedback) Design, solves the problem of choosing desired closed loop eigenvalues, with the remaining degrees of freedom arbitrarily assignable to influence closed loop properties. This design method has been extensively studied in the time domain using state equations.

State feedback control can equally be parametrized in the frequency domain on the basis of matrix fraction descriptions for the system transfer matrix. The polynomial matrix $\tilde{D}(s)$, parametrizing the state feedback in the frequency domain, contains the same amount of free parameters as the state feedback matrix K, namely nm.

We here present a method allowing to choose $\tilde{D}(s)$ such that the closed loop poles have desired locations, while the remaining $(m-1)n$ free parameters in $\tilde{D}(s)$ can arbitrarily be chosen without hazarding closed loop stability. This uses the so-called Pole Directions, also called eigenvectors or characteristic vectors of $\tilde{D}(s)$. It is shown, how the Pole Directions are related to the eigenvectors used in the time domain approach, and it turns out, that the computation of an equivalent K, given a $\tilde{D}(s)$, can be simplified using Complete Modal Synthesis.

A. ILCHMANN

Robustness of slowly time-varying linear systems with applications to gain scheduling

It is proved that the stability radius (w.r.t. causal L_2-operators) of time-varying linear systems is bounded from below by $\rho-\epsilon > 0$ provided that the stability radii of the 'frozen' systems are bounded from below by $\rho > 0$ and the time variation is sufficiently small. This is applied to gain scheduling to show that the trajectory within the compact flight envelope is practically stable.

A. ISIDORI

Stabilization using output feedback

Many of the methods currently available for robust stabilization of nonlinear system using output feedback rely upon the hypothesis that the system has a stable zero dynamics. The main reason why this hypothesis is assumed is that the methods in question use 'high-gain' feedback in order to offset the presence of certain unwanted terms in the dynamics of the closed-loop system. The consequence of this high-gain control is to enforce a behavior whose asymptotic properties are directly influenced by the asymptotic properties of the zero dynamics.

In this lecture, we have presented a new method which does not rely upon such a construction. Rather, it aims at taking advantage of the terms which connect the zero dynamics to the equation in which the control enters explicitly. More precisely, consider a system modeled by equations of the form

$$\begin{aligned} \dot{z} &= f(z, y, p) \\ \dot{y} &= h(z, y, p) + u \end{aligned} \tag{1}$$

where $z \in I\!R^{n-1}$, $y \in I\!R$, p is an uncertain parameter and $u \in I\!R$. The output y is the only variable accessible for feedback. It is shown that if the auxiliary system

$$\begin{aligned} \dot{z} &= f(z, \bar{u}, p) \\ \bar{y} &= h(z, \bar{u}, p) \end{aligned} \tag{2}$$

with input $\bar{u}$ and output $\bar{y}$ is stabilizable by (dynamic) output feedback, the original system (**??**) is semi-globally practically stabilizable by dynamic output feedback.

H. W. KNOBLOCH

On dissipation inequalities

Dissipation inequalities serve as a principle for regulator design for control systems which are influenced by exogenous disturbances. If one associates with the problem of disturbance attenuation a differential game ('worst case philosophy') then the saddle point condition gives rise to a dissipation inequality. The lecture presents a new angle on dissipation inequalities which is of interest in a special situation, namely:

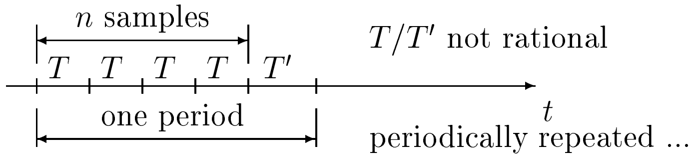
(i) The time horizon is infinite.
(ii) The dynamical law can be decomposed in two parts, the second one is not directly influenced by the disturbance.
(iii) The disturbance is bounded in norm, but not necessarily square integrable over $[0, \infty)$.
(iv) The mathematical model is time-continuous, the control law however is discretized.

The main result is a general inequality involving integrals from which one can derive both dissipation inequalities and statements concerning stabilization of control systems. The essential feature of this result is the absence of discretization errors, hence it is an example of a robust solution of design problems.

G. KREISSELMEIER

Safe sampling

It is shown that with non-equidistant, periodic sampling of the form



the discretization of n-th order linear time-invariant systems is always without loss of controllability and observability.

A. J. KRENER

Nonlinear Observers

The term 'nonlinear observer' for a dynamical system with output has several meanings. In a narrow sense of the term, it refers to a second dynamical system of the same state dimension as the given system which, driven by the output, asymptotically tracks the given system. In a broader sense, it refers to second dynamical system of different dimension which asymptotically tracks the first. For nonlinear systems, the observer is frequently infinite dimensional. In its broadest sense it refers to any rule for processing the part observations to arrive at an estimate of the current state.

We present joint work with W. Kang, the Naval Postgraduate School, Monterey, California. A backstepping approach is used to construct narrow sense observers for a large class of nonlinear dynamical systems. This can be generalized to a method for constructing observers in the broader sense for a large class of systems. These observers are exponentially convergent over compact domain of the original system provided the initial estimation error is not too large. In the high gain limit they converge to the high gain observer of Gauthier, Hammouri and Othman.

We close with two examples of one dimensional systems which do admit convergent narrow sense observers. The first is analytic and does not have a globally convergent observer. The second is C^∞ and does not admit a locally convergent observer.

A. KURZHANSKI

On the reachability problem for controlled processes

The presentation was devoted to three issues:

'Ellipsoidal techniques for reachability analysis': Here it was demonstrated that the tightest ellipsoidal approximations for reach sets generated by linear systems with hard bounds could be calculated through a system of explicit ODEs with parameters governed by the adjoint system.

'Reachability and the HJB equation': The possibility of calculation reach sets as the level sets to a generalized solution of a forward HJB equation was demonstrated and some propositions on HJB-type inequalities were formulated.

The issue of 'reachability under uncertainty' was discussed for linear systems with hard bounds on the uncertain inputs. The respective sets were presented as the cross-sections of the value functions of a forward HJBI equation. Some illustrations of graphic simulations were also demonstrated.

H. KWAKERNAAK

An improved algorithm for the solution of the H-infinity problem for descriptor systems

H_∞ optimization is a powerful tool for control system feasibility and design studies. Representing the generalized plant in descriptor form provides a very flexible and general way of defining and handling many useful and practical H_∞ optimization problems.

The frequency domain solution of the standard H_∞ optimization problem leads itself very well for the solution of the H_∞ problem for descriptor systems. It reduces the computation of suboptimal compensators to a spectral factorization of a rational matrix in descriptor form.

The key to the computation of the spectral factorization is the transformation of two symmetric matrix pencils to triangular form, known as the Clements form. These transformations correspond to the solution of the two well-known Riccati equations for the state space H_∞ problem, which in turn may be reduced to the transformation of two Hamiltonian matrices to Schur form.

By suitably arranging the spectral factorization the unnecessary but critical matrix inversions that cause the notorious numerical ill-conditioning problems of the state space solution may easily be avoided. In fact, the singularity condition that causes this phenomenon may be exploited to speed up the convergence of the iterative search procedure for the optimal solution, thus facilitating the accurate computation of optimal solutions.

The algorithm has been implemented as part of the Polynomial Toolbox for MATLAB. It is demonstrated by computing least upper bounds for the infinity norm of the sensitivity matrix of MIMO feedback systems with right-half plane poles and zeros.

H. LOGEMANN

Absolute stability results for infinite-dimensional systems with applications to low-gain control

In this joint work with R. F. Curtain (Groningen), we derive absolute stability results for regular linear infinite-dimensional systems, which, in a sense, complement the well-known circle criterion. These results are used to derive convergence and stability properties of low-gain integral feedback control applied to exponentially stable linear regular systems subject to actuator nonlinearities lying in a nonnegative sector. The class of regular linear systems includes most distributed parameter systems of interest in applications; in particular, it allows for considerable unboundedness of the control and observation operators.

J. LÜCKEL

Mechatronic design of the new triplanar machine for highly precise process- and measurement tasks

Triplanar is the name for a new measurement and processing machine. The idea for the design of the machine with new parallel kinematics came up at the Mechatronics Laboratory Paderborn early in 1998. Due to the complexity of the kinematics as well as the force actuation the development of the machine has to be supported by means of an extended computer-aided design. By comparing the conventional geometric design method (CAD) with the so-called mechatronics design method, it is shown that an optimal design of all devices (both hardware and software) can only be reached by applying the mechatronics design method. The core of this method is the consideration of the overall system dynamic behaviour including the interaction of all components involved.

The Triplanar is being developed in a cooperation between the MLaP (Prof. Lückel), the IMM of the TU of Ilmenau (Prof. Kallenbach) and the IFM of the TU Chemnitz (Prof. Maißer). The hardware components of the Triplanar prototype will be realized in the middle of 1999.

J. LUNZE

Representation of quantised systems by semi-Markov processes with application to process diagnosis

The paper concerns linear continuous-variable systems whose state can only be observed through a quantiser which indicates the time instant and the direction of the change of the quantised state value. These changes are considered as events. The problem is to find a concise representation of the quantised system which allows to determine for a given initial event all timed event sequences that the quantised system can generate. Since the quantised system does not possess the Markov property, the modelling aim is to find a semi-Markov process which describes a superset of the event sequences of the quantised system. The paper shows how such a Markov model can be obtained for a given quantised system. The model provides information about the absolute occurrence time of the events and about the probability of the occurrence. The suitability of the semi-Markov process for solving supervisory control tasks is illustrated by solving a diagnostic problem by means of this representation of a quantised batch reactor.

M. MANSOUR

Robust stability of time varying systems

The Kharitonov robust stability problem is extended to time varying systems where the parameters have upper and lower limits (i.e. lie in a box in the parameter space) and the rate of change of the parameters has also upper and lower limits (i.e. lies in another box in the derivative space). Alternate problems are:

1) Given the region of stability in the parameter space, find the upper limit for the rate of variation of the parameters.
2) Given the upper limit of the rate of variation, find the region of stability in the parameter space.

For the solution of these problems three mathematical tools are used, namely: Method of Norms, Lyapunov function method and the poles of linear time varying systems according to Kamen (1988). The results obtained by the first and third method are discussed showing how a relatively large region of stability is obtained given the limit of variation of the parameters especially for a second order discrete system.

W. MATHIS

Stochastic analysis of nonlinear electrical networks with thermal noise

In this talk we consider the problem of internal noise in nonlinear electrical networks and show that this kind of disturbances cannot be represented by external noise sources what is common in electrical network theory. Some concepts of system dynamics with density functions are discussed. Then a more general Markov approach is formulated using a Kramers-Moyal equation which was founded by Stratonovich in the early nineties. Based on this a theory of thermal noise in nonlinear reciprocal networks is derived where this class of networks are described by the Brayton-Moser equations. As a result a systematic approximation in terms of $(kT)^n$ can be extracted that is of the form of a Fokker-Planck equation. An example illustrates this approach. Some consequences for a theory of noisy nonlinear networks will be discussed. This is a joint work with L. Weiss.

G. MEINSMA

Inverse optimal loopshaping

A popular approach to controller synthesis is to see it as a the problem of shaping the loop gain $L(j\omega)$ or, the sensitivity function $S(j\omega)$ and complementary sensitivity function $T(j\omega)$. One way to achieve this is to use optimization methods such as H_2 and H_∞ optimization.

Such optimization methods are of limited use if they can not be generate controllers of which we know that they work well in closed loop. Optimization methods should be able to reach a large class of 'desirable' controllers if these methods are to become of practical use.

We approach this problem through the inverse optimization problem. That is, given a controller we ask ourselves if this controller can be the result of an optimization method. We distinguish and compare H_2-norm optimality, H_∞-norm optimality and one- and two-block problems.

M. MORARI

A Framework for Control, State Estimation and Verification of Hybrid Systems

This is a joint work with Alberto Bemporad, Domenico Mignone, Giancarlo Ferrari-Trecate and Fabio Danilo Torisi. We propose a framework for modeling systems described by interdependent physical laws, logic rules, and operating constraints, denoted as Mixed Logical Dynamical (MLD) systems. These models consist of linear dynamic equations subject to linear inequalities involving real and integer variables. MLD systems include constrained linear systems, finite state machines, some classes of discrete event systems, and nonlinear systems which can be approximated by piecewise linear functions. We pose the problems of reachability/controllability/verification, observability/reconstructibility, optimal control, estimation and fault detection in this context. We show that within the MLD framework all these problems lead to Mixed Integer Linear or Quadratic Programs (MIQP), for which efficient solvers have been developed, recently. Specifically, a predictive control scheme is proposed which is able to stabilize MLD systems on desired reference trajectories while fulfilling operating constraints, and possibly take into account previous qualitative knowledge in the form of heuristic rules.

P. C. MÜLLER

Convergence of the estimation of nonlinearities by linear state observers

Since years there is an experimental experience how unknown nonlinear effects of a dynamical system can be estimated by linear state observers. For this, the time behaviour of the nonlinearities is approximated by base functions which are generated by a set of LTI-ODE of first order. Using this approximation, an extended linear system appears for which an observer is designed. The observer states represent estimates for the system states and for the nonlinear behaviour. Although in practice this method is successfully applied for the compensation control and for the detection of faults, a rigorous mathematical foundation is still missed. Here, two approaches for the convergence of the method for high observer gains are shown. Certain open problems within the proofs are discussed in detail.

H. NIJMEIJER

System identification in communication with chaotic systems

Communication using chaotic systems is considered from a control point of view. It is shown that parameter identification methods may be effective in building reconstruction mechanisms, even when a synchronizing system is not available. Three worked examples show the potentials of the proposed method, these include the standard Chua circuit and the Rössler system.

H. NOUR ELDIN

Kovács-Zustandsraum und seine Erweiterung (quaternionisch) für die Synchrongeneratordynamik

The d-q-axis formulation of the synchronous generator dynamics (IEC-Model) in the state vector form is well established and has been used in numerous applications especially in simulation and control. Beside this mainstream of modelling of the AC machine dynamics, the complex space vector theory of 'Kovács' and 'Ràsz' has been used, mainly for AC drives. Some advantages of this space vector theory are obvious. However, it was not possible to model non d-q-symmetrical AC machines like the synchronous generator. Also, the introduced complex space unit remained intuitive.

In the first part of the lecture, the d-q-axis theory is reformulated using the algebra of space hypercomplex and quaternions. Then, this algebra is reduced to the space z-complex algebra, where z is the unit orientation of the prime mover. The AC machine power quaternion and air gap quaternion are introduced. It is shown that only when the AC machine is completely d-q-symmetric, it is possible to express its dynamics by a second (third) order space z-complex state equation. For the general IEC-Model, the flux-current relation includes the space conjugate of the current. By introducing the symmetry/asymmetry reactances and resistances, the space z-complex representation of the general IEC-Model is achieved.

The second part of the lecture is devoted to the inherent algebraic structure of the AC machine. It is shown that the basic algebraic structure of the flux current relation is the finite cyclic group ($\epsilon^2 = 1$). The resulting reactance matrix can be represented by the double number ϵ-algebra. The flux current relation as well as the IEC-Model dynamics can be represented by the space z-complex variables whose coefficients are double numbers. This representation exploits the d-q symmetry or asymmetry in a direct manner. Alternatively, the clifford projection units will be used with the advantage that the d-q coil geometry of the AC machine is algebraically described. Finally, a novel d^*-q^* two axis model of the synchronous generator dynamics is presented. This model is the generalization of the Kovács and Ràsz theory for a general AC machine. For a symmetrical AC machine, it reduces to the Kovács-Ràsz-Model.

G. J. OLSDER

Control of traffic

This talk consists of two parts. The first one is an explanation of the Braess paradox in terms of the Nash and Pareto equilibrium concepts. The paradox deals with a saturated road structure on which drivers choose their fastest route towards their destinations. It turns out, depending on parameters determining the travelling times, that closing some parts of the road structure leads to better results for all drivers.

The second part deals with the max-plus algebra approach to the synchronization of traffic lights such as to get as many – possibly interacting – green waves as possible. This has been applied to the city of Delft. Choosing the lights in an appropriate time order was compared to the design of a time table for a railway company. In this comparison, a crossing coincides with a station and a platoon (of cars) with a train. In both applications the notations of eigenvector and eigenvalue in the max-plus algebra play an essential role.

R. ORTEGA

Benchmark examples on energy transformation systems

Towards the aim of developing a performance-oriented theory for nonlinear systems with physical constraints we propose the development of a suite of benchmark examples taken from subareas of power electronics, power systems and electric drives. The point is illustrated with the analysis and design of switched controllers for induction motors. In particular, a detailed analysis of the popular Direct Torque Control is provided.

W. RESPONDEK

On geometry of non-holonomic control systems described by Goursat structures

There has been an increasing interest, during the last ten years, in non-holonomic control systems. Many of those systems are described by Goursat structures. The latter are rank-2 distributions whose derived flag of distribution is regular and of minimal growth. At regular points Goursat structures are equivalent to Goursat normal form, called 'chained form' in control theory. Based on this, many control problems (e.g., pointwise stabilization, motion planning, trajectory tracking, modal matching) have been successfully solved. Those nice solutions sometimes fail to work: At singular configurations, for some singular controls, and for domains which are 'too large'.

The aim of the talk was to describe these singularities. For singular configurations, the basic result is that of Kumpera-Ruiz giving normal form for Goursat structure. We discuss this classification in small dimension and illustrate it by the benchmark example of the n-trailer (a mobile robot with n trailers). We give a general result concerning the local classification: Up to $\mathbb{R}^8$, the growth vector is a complete invariant, it stops to be in $\mathbb{R}^9$, in $\mathbb{R}^{10}$ (and higher dimensions) there are real parameters in the classification, but in any dimension Goursat structures are finitely determined. Then we discuss singular trajectories of the problem rigid curves (isolated in C^1-topology). We give a complete description of them and illustrate them in the case of the n-trailer: The rigid curves are those which leave at least one of the trailers invariant in the (x-y)-plane. Finally, we discuss exotic structures and show that the non-holonomic case is exotic (not transformable globally to the Eagel form). We finish by a surprising result: Any Goursat structure is locally equivalent to the n-trailer at a well chosen configuration: The n-trailer is then a universal model for all Goursat structures.

K. SCHLACHER

Geometric control of nonlinear descriptor-systems

This contribution presents methods for the geometric control of a special class of nonlinear control systems called descriptor-systems. They are described by implicit ordinary differential equations, which are linear in their time derivatives. Although descriptor-systems look similar to explicit control systems owing to a common notation one uses them to describe a much wider class of dynamical systems.

Explicit control systems allow to separate the state and control input in a straightforward manner. This approach, although often used, is too restrictive for descriptor-systems. It can be shown that the implicit system can be transformed to an intermediate one in the neighborhood of a generic point, that resembles an explicit control system as much as possible. Based on this intermediate form one can separate state from control input and do further investigations concerning accessibility, observability, input-to-output or input-to-state linearization or the check, if the descriptor-system is transformable to an affine input system. It is worth to mention that the proposed methods and algorithms can be implemented easily in a computer algebra program.

K. R. SCHNEIDER

Control of exchange of stabilities

We consider nonlinear and continuous and discrete control systems depending on a parameter vector λ. We assume the existence of critical parameter values at which an exchange of stability of limit sets of the corresponding uncontrolled dynamical system takes place. If the bifurcation parameter λ is slowly varying in time (dynamic bifurcation), then a delayed exchange of stabilities can occur which is related to a fast transition (jump behaviour). In the lecture we derive methods to stabilize fixed points of discrete control systems by means of state-parameter feedback control, and we present an approach to steer an exchange of stabilities related to dynamic Hopf bifurcation. The results are based on the study of singularities of higher codimension.

M. ŠEBEK

Numerical algorithms for polynomial matrices – recent progresses

Polynomial methods are now a well-established part of linear control theory. Current research effort concentrates namely in improving numerical procedures for computation with polynomial matrices.

Classical numerical algorithms are reviewed in the talk and their properties are discussed. Then two new methodologies are presented that lead to more efficient and more reliable routines and hence are more suitable for industrial control design. One group of new method is based on systematic use of Sylvester matrices. It yields, e.g., the first numerically stable procedure for triangularisation of a polynomial matrix. The second group employs Fast Fourier Transform that leads to drastical improvement in computation of determinant, adjoined and rank of polynomial matrices. All the algorithms presented are demonstrated on-line via Polynomial Toolbox 2.0 for Matlab 5, a product of PolyX, Ltd.

O. STRUSBERG

Discrete modelling of continuous processes for the verification of event-driven controllers

Recently, some effort has been spent on making the verification techniques known from computer science applicable to the design of event-driven controllers. The idea is to show (predominantly by reachability analysis within a discrete state space) that the controller behaves correctly with respect to a given specification, i.e. it prevents a system from reaching a set of *forbidden* states. A precondition for the application of verification methods is a purely discrete model of the system, or a model which contains only very simple continuous dynamics, as e.g. clocks. The talk will focus on the generation of such *verifiable* models from a system representation which suitably captures the continuous or hybrid behaviour of a process. In detail, we propose discretization methods to transform a special class of hybrid systems, so-called Switched Continuous Systems, into Timed Automata respectively Rectangular Automata (for which reachability analysis is decidable). Four different discretization approaches which are settled on degrees of abstraction ranging from qualitative modelling to a procedure based on numerical integration are proposed. The properties completeness, consistency and complexity of the model transformation are discussed since these are important for the results of the reachability analysis. The overall procedure will be illustrated by application to a simple technical example, a controlled chemical reactor.

H. J. SUSSMANN

Recent results on the maximum principle with applications to some very old problems

A recent version of the maximum principle works for general flows (i.e. families

$\{\Phi_{t,s}\}_{s\le t,\ s,t\in I}$ of set-valued maps, indexed by pairs $(s,t)\in I\times I$ such that $s\le t$, where I is a totally ordered set, that satisfies the identities $\Phi_{t,t}=id$, $\Phi_{t_1,t_2}\circ\Phi_{t_2,t_3}=\Phi_{t_1,t_3}$) that are 'differentiable' in a generalized sense along a trajectory of the flow. This version is valid for any 'generalized differentiation theory' (GDT) that satisfies a transversal intersection property. Various classical versions of the principle, such as those of Pontryagin, Clarke and S. Lojasiewicz Jr. are obtained by specializing to a suitably chosen GDT. The new general version is applicable to 'hybrid' problems and systems with discontinuities. In particular, several old problems (e.g. reflection, refraction, and the reflected brachystochrone) now fall within the scope of the general theory and can be handled without resorting to ad hoc arguments.

M. ZEITZ

Design of distributed parameter observers

The structure of distributed parameter observers follows by extension of the Luenberg approach to infinite dimensional systems described by partial differential equations (pde) and boundary conditions (bc). The observer correction can be injected both into the pde and into the bc. The considered late lumping design of the corrections is based on the physical insight of the distributed parameter observer error dynamics. In the nonlinear case, an extended linearization is applied on the error dynamics. The observer design is illustrated for a linear heat conduction system and for nonlinear models of a multizone furnace and of a chemical circulation loop reactor.

E. ZERZ

On strict system equivalence for multidimensional systems

The notion of strict system equivalence was introduced by Rosenbrock (1970) and subsequently refined by Fuhrmann (1977). It describes the connection between all least order realizations of a transfer matrix in terms of a general constant linear differential system

$$T\;x=U\;u,\qquad y=V\;x+W\;u, \tag{1}$$

where T,U,V,W are polynomial matrices in the 'indeterminate' $\frac{d}{dt}$. This talk generalizes this and related notions and properties to the case of multidimensional systems, i.e., linear systems of partial differential (or difference) equations with constant coefficients. The main difficulty is the fact that the usual notion of a right coprime factorization of a transfer matrix, say $H=ND^{-1}$ with polynomial matrices N and D, D non-singular, becomes restrictive for systems of dimension greater than two (Oberst 1990). Non-square 'denominator' matrices D have to be admitted and consequently, rectangular 'T-matrices' have to be considered in (**??**).

Report written by T. LILGE

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