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Scientific Program - Timetable

Sunday 22	Time	Monday 23	Tuesday 24	Wednesday 25	Thursday 26	Friday 27
	9:00		Contributed sessions (15 in parallel)	Plenary Lecture Moritz Diehl	Contributed sessions (15 in parallel)	Contributed sessions (14 in parallel)
	9:30					
	10:00	Registration		von Mises prize lecture		
	10:30					
	11:00		Coffee Break	Coffee Break	Coffee Break	Coffee Break
	11:30		Plenary Lecture Thomas Böhlke	General Assembly	Plenary Lecture Ferdinando Auricchio	Contributed sessions (11 in parallel)
	12:00					
	12:30		Lunch	Lunch	Lunch	
	13:00	Opening				
	13:30	Univ. Chorus Performance				Closing
	14:00	Prandtl Lecture Keith Moffatt	Plenary Lecture Enrique Zuazua	Contributed sessions (15 in parallel)	Plenary Lecture Daniel Kressner	
	14:30					
	15:00	Plenary Lecture Giovanni Galdi	Plenary Lecture Nikolaus Adams		Plenary Lecture Stanislaw Stupkiewicz	
	15:30					
Registration pre-opening	16:00	Coffee Break	Coffee Break Poster session	Coffee Break	Coffee Break Poster session	
	16:30	Minisymposia & Young Reseachers' Minisymposia (10 in parallel)	Contributed sessions (14 in parallel)	Contributed sessions (15 in parallel)	Contributed sessions (15 in parallel)	
	17:00					
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	18:30		Public lecture Francesco D'Andria			
	19:00	Opening reception at Castle of Charles V				
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GAMM 2015

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S20: Dynamics and control

Dynamics and control is an interdisciplinary section which in particular adresses mathematical systems theory and control engineering. The contributions to this section are also concerned with the mathematical understanding of the dynamics of controllers which appear in actual applications.

Control design of the vibration reduction systems

Igor Maciejewski, Tomasz Krzyzynski
Departament of Mechatronics and Applied Mechanics
Faculty of Technology and Education
Koszalin University of Technology
Sniadeckich St. 2, Koszalin, 75-453 PL

The paper deals with an original control algorithm for semi-active and active suspension that are often used in automotive systems. The developed procedure assists in finding the structure of control system, which can predict the desired active force, is able to adapt to various working conditions and is robust in response to varying mass loading of the suspension system. The control system consists of the primary controller that calculates the desired active force. Then the desired force has to be approximately achieved by the semi-active or active element with calculated input signal using the reverse model [1]. The PD predictor speeds up the semi-active or active system control because the actuating time of the force actuator is partly eliminated.

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Coordination of guidance and stabilization tasks for bicycle rider modelling

Johannes Edelmann, Martin Haudum, Manfred Plöchl
Institut für Mechanik und Mechatronik
Technische Universität Wien

Based on a nonlinear mathematical bicycle–rider model, this study aims to contribute to understanding the steering behaviour of a bicycle rider. In contrast to automobile drivers at regular driving conditions, the bicycle rider has to stabilize the motion of the bicycle at low velocities to prevent toppling over, see e.g. [1], in addition to guiding the vehicle along the desired trajectory. The human bicycle rider may accomplish these tasks by applying steering torque, roll torque or movement of his/her knees, [2]. As the dynamic response of the yaw rate and steering angle to a steering torque input, see e.g. [3], or roll torque input shows in general non-minimum phase characteristics, the control bandwidth is limited to low frequencies. Thus, the guiding capabilities of the bicycle rider are restricted by this bandwidth limitation. Considering the stability properties of the system at low velocities, in addition, the rider has to stabilize the motion of the bicycle. Hence, the control requirements of the bicycle–rider system become even more demanding.

In this study, the controllability of the bicycle–rider system is investigated by applying either steering or roll torques, and consequences of the characteristic dynamic behaviour of the system on the bicycle rider control demands are addressed. Based on findings on the control behaviour of aircraft pilots and automobile drivers, a three-layer bicycle rider model is presented that aims to mimic the human rider control behaviour. The steering behaviour is represented by an anticipatory feed-forward control layer and a compensatory feedback control layer to guide the bicycle along a desired trajectory, and a stabilizing feedback control layer to stabilize the motion of the bicycle within its unstable velocity range. While the feed-forward control layer is based on the 'ideal driver', [4], different approaches to represent both the compensatory and stabilizing feedback control layer are discussed considering human cognition and motor capabilities.

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Parameter identification of a scaled experimental running gear

Alexander Keck*, Christoph Schwarz*
*German Aerospace Center, Institute of System Dynamics and Control, Oberpfaffenhofen

For the development of a mechatronic track guidance system in the DLR project "Next Generation Train" steerable, individually powered, independently rotating wheels (IRW) are favored [2]. This configuration offers optimal radial adjustment between the rolling and moving direction. Thus unnecessary creep in the wheel rail contact is avoided and a significantly reduced wear is expected especially in tight curves [1]. To test the system behavior and develop appropriate control algorithms for the mechatronic track guidance system, an experimental running gear for the existing 1:5 roller rig was designed and manufactured at DLR. The running gear is equipped with several measurement devices such as laser position and force/torque sensors. In addition, the DLR RailwayDynamics Library implemented in the simulation environment Modelica/Dymola is used to model and simulate the behavior of the scaled running gear [3].

In order to receive a simulation model, that coincides with the real running gear in the frequency range of interest, it is necessary to quantify the characteristic parameters of the system. To this aim several methods have been applied in this work: CAD data were utilized, specific parameters of the system were measured individually and the system behavior in simulation and experiment were compared by exploiting the comprehensive sensor data of the test rig. Individual measurements were preferred to identify the stiffness of the virtual rotational spring, which acts around the z-axis between the wheel-carrier and the frame. This effect is not only based on the vertical primary suspension of the running gear but also influenced by the parasitic friction of the motor cables going from the frame to the wheel-modules.

In order to explore the technical boundaries of the wheel hub motors a pseudo random binary sequence (PRBS) is used to determine their dynamic properties. On the basis of these measurements a transfer function for each of the four wheel hub motors is built and introduced in the simulation model. Finally an optimization task was performed in which experimental results of the running gear on the test rig were compared with simulation results in order to adjust additional parameters. The presentation of the initial control design of the running gear and its behavior in simulation and experiment will conclude the presentation.

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Nonlinear control of a variable displacement vane pump

Marius Köster, Alexander Fidlin
Institut für Technische Mechanik, Karlsruher Institut für Technologie

Variable displacement vane pumps are used for mid-pressure applications in a variety of systems. Due to their potential for power loss reduction they are most prominently featured in automotive applications. Variable displacement vane pumps provide a hydraulic consumer with varying levels of volume flow, depending on the eccentricity of the pump. Eccentricity control is typically achieved by means of hydraulic actuation. For some applications, hydraulic actuation is a result of an appropriate choice and design of self-regulating valves. For more advanced applications, servo valves can be utilized - allowing for a more sophisticated control of the systems. As hydraulic systems are inherently nonlinear due to the physics governing the processes involving hydraulic elements, adequate control strategies should take these nonlinearities into account. In practice, most control strategies in hydraulic systems have remained linear despite the advances in nonlinear control during the past decades, resulting in suboptimal performance of the controled systems. However, successfull application of nonlinear control strategies in the context of hydraulic systems has been reported [1], [2]. Therefore, in this contribution a volume flow control strategy based on input-output linearization [4] of a variable displacement vane pump system is suggested.

The system at hand consists of a variable displacement vane pump, a load modeled by a hydraulic resistance and a servo valve. Assuming an ideal valve with no dynamic behavior, the system can be represented by a four state system model. Because the pump is actuated by volume flow provided by the pump itself, the pump system dynamics are intricate and feature a switching behavior in correspondence with desired increases or decreases in volume flow. To describe the switching behavior, two sub systems are introduced to the system description. In order to compensate the system's switching behavior, an input-output linearization is performed for each of the sub-systems. The relative degrees of the sub-systems are identical with $r = 3$, leaving stable zero dynamics in the form of volume flow balances that are subject to the switching behavior of the system. A linear controller is then applied to the partially linearized system, yielding asymptotic trajectory tracking behavior in accordance with the requirements.

Based on the Byrnes-Isidori normal form, a normal form observer following Roebenack [3] then is constructed in order to obtain the states required for the nonlinearity-compensating feedback. The validity of both control and observation strategy are shown in simulations.

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A kinematic approach based on an equivalent track for a skid-steering robot

Rocco Galati, Nicola Ivan Giannoccaro, Arcangelo Messina, and Giulio Reina
Università del Salento, Dipartimento di Ingegneria dell'Innovazione
Via per Monteroni 73100, Lecce, Italy
e-mail: rocco.galati@unisalento.it

The skid steering principle is based on controlling the relative velocities of both the tracks as differential drive wheeled vehicles. However, control of tracked locomotion poses a more complex problem because variation of the relative velocity of the two tracks results often in slippage of the vehicle. This contribution propose a kinematic approach for improving the motion control and dead-reckoning of a skid-steering robot, considering the effects of the slippage but without introducing the complexity of dynamics computation. This problem has been recently tackled by researchers and some experimental results for some types of tracked robots have reported in [1], [2], [3], [4].
The equivalent track approach has been here applied to a skid-steering robot (Husky A200), characterized by an high maximum payload (75 kg) and by a high power than makes it able to move in very difficult conditions (snow, iced terrains, etc.), where the slippage effects become predominant. The equivalent track of the kinematic model has been identified by means of several experimental tests with different velocities of the robot wheels measured by integrated encoders. The equivalent track model has then been used for outdoor tests in closed loops; the odometric estimation results are encouraging showing very low errors in the reconstruction of the trajectory. Details about the robots characteristics, the approach algorithm and the experimental results will be given in the presentation and in the full paper.

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Harmonic Mistuning of Blisks

Linus Pohle, Lars Panning-von Scheidt, Jörg Wallaschek
Institute of Dynamics and Vibration Research
Leibniz Universität Hannover
Appelstr. 11, 30167 Hannover, Germany

Manufacturing tolerances and wear cause small deviations of the turbine blades' geometry. Such damage to the cyclic symmetry can effect a significant amplification of the vibration amplitudes. To estimate the maximum vibration amplitude, two common methods are useable. On the one hand, the limit for the overall maximum vibration amplitude can be calculated using the WHITEHEAD factor [1]. This factor overestimates the amplitude of a random mistuning pattern. On the other hand, Monte-Carlo simulations are used to estimate the maximum amplitude of the given blade tolerances [2]. This method is very time-consuming and requires high computational effort.
The full length paper describes a new method to calculate the maximum amplification of a given manufacturing tolerance. Two effects of mistuned blisks are analyzed in this paper. The separation of two orthogonal nodal diameters could be shown and described in detail. Furthermore, the excitation of more than one nodal diameter by only one engine order could be found. If the eigenfrequencies of these nodal diameters are close together, the vibration amplitude of some blades increases. Based on a lamp-mass model, it is shown which maximum amplitude can be achieved. The idea is to use a harmonic mistuning pattern to get the highest influence at small tolerances for one single nodal diameter. This influence cannot be beaten by a randomly mistuned system and limits the maximum amplitude. The given analysis is validated by a common Monte-Carlo simulation. Based on this analysis, the benefits of an intentional mistuning are shown. Due to the separation of the nodal diameter, the vibration amplitude is robust towards small mistuning tolerances. Furthermore, it is possible to split off close nodal diameters to prevent mode interaction.

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Stability analysis of implicit difference equations

V. Mehrmann[1], D.D. Thuan[2]
[1]TU Berlin, [2]Hanoi University of Science and Technology

The stability analysis for linear implicit m-th order difference equations in descriptor form is discussed. We allow the leading coefficient coefficient to be singular, i.e., we include the situation that the system does not generate an explicit recursion. A spectral condition for the characterization of asymptotic stability is presented and computable formulas are derived for the real and complex stability radii in the case that the coefficient matrices are subjected to structured perturbations.

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Controllability characterization for switched DAEs

Ferdinand Küsters, Stephan Trenn
University of Kaiserslautern, Germany

Switched differential algebraic equations (switched DAEs) of the form

$$E_\sigma \dot{x} = A_\sigma x + B_\sigma u$$

with switching signal $\sigma : \mathbb{R} \to \{1, 2, \ldots, N\}$ play an important role when modeling systems with algebraic constraints subject to sudden structural changes, for example electrical circuits with switches. Controllability is a fundamental systems property and is concerned about the ability to reach any final feasible state from any initial feasible state. Based on the single switch result presented at the previous GAMM Annual Meeting [1] the controllability characterization will be generalized to the general case. Furthermore, several examples are presented which highlight special features of controllability for switched DAEs, for example, the dependence of the switching times as well as the ability for instantaneous control. Some pitfalls leading to some incorrect statements in [1] are also highlighted.

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The Kalman-Yakubovich-Popov Inequality for Differential-Algebraic Equations

Timo Reis[1], Olaf Rendel[1], Matthias Voigt[2]
[1]Universität Hamburg, Fachbereich Mathematik
[2]Technische Universität Berlin, Institut für Mathematik

The Kalman-Yakubovich-Popov lemma is one of the most famous results in systems and control theory. Loosely speaking, it states equivalent conditions for the positive semi-definiteness of a so-called Popov function on the imaginary axis in terms of the solvability of a certain linear matrix inequality, namely the Kalman-Yakubovich-Popov (KYP) inequality. In applications, this lemma plays an important role in assessing feasibility of linear-quadratic optimal control problems or characterizing dissipativity of linear control systems.

In the literature, there exist manifold attempts to generalize this lemma to differential-algebraic equations. However, most of these approaches make certain restrictive assumptions such as a bounded index or impulse controllability. In this talk we show how to drop these restrictions by considering the KYP inequality on the system space, i.e., the subspace in which the solution trajectories of the system evolve. Moreover, we present results on the solution structure of this inequality. In particular, we consider rank-minimizing, stabilizing, and extremal solutions. These results can then be interpreted as a generalization of the algebraic Riccati equation to a very general class of differential-algebraic control systems, see [1, 2] for details.

References

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Controlled invariance for DAEs

Thomas Berger
Universität Hamburg, Germany

We study the concept of locally controlled invariant submanifolds for nonlinear descriptor systems. In contrast to classical approaches, we define controlled invariance as the property of solution trajectories to evolve in a given submanifold whenever they start in it. It is then shown that this concept is equivalent to the existence of a feedback which renders the closed-loop vector field invariant in the descriptor sense. This result is motivated by a preliminary consideration of the linear case.

Local controlled invariance leads to the concept of output zeroing submanifolds. We show that the outcome of the differential-algebraic version of the zero dynamics algorithm yields a maximal output zeroing submanifold. The latter is then used to characterize the zero dynamics of the system. In order to guarantee that the zero dynamics are locally autonomous (i.e., locally resemble the behavior of an autonomous dynamical system), sufficient conditions involving the locally maximal output zeroing submanifold are presented.

Control of underactuated systems with coupling input forces

Sebastian Korczak
Warsaw University of Technology

The dynamic system is called underactuated if unlimited control inputs cannot produce any system accelerations. The most popular reason of that is a lesser number of inputs than the number of degrees of freedom. Current review of underactuated systems and their control is presented in [1]. Trajectory tracking and stabilization problems are usually solved with backstepping technique [2], sliding mode [3] or optimization methods. In these problems, the partial feedback linearization method and system flatness property are useful.

This contribution is focused on problem of interacting inputs, which occur e.g. in VTOL aircraft, copter, surface vessel or underactuated mobile platform models. Most researchers simplify analyzed models to obtain noncoupling inputs. A few articles [4] present control of systems with coupled inputs by using control law only for noncoupled state variables and verifying behavior of remaining variables. We propose a method for control of all system state variables with coupled inputs based on the computed torque technique combined with stability analysis [5].

References

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Stabilization using discounted optimal control problems

Vladimir Gaitsgory[1], Lars Grüne[2], Neil Thatcher[3]
Department of Mathematics, Macquarie University, NSW 2109, Australia[1]
Mathematisches Institut, Universität Bayreuth, 95440 Bayreuth, Germany[2]
Weapons and Combat Systems Division, Defence Science and Technology Organisation
Edinburgh SA 5111, Australia[3]

Since the invention of the linear-quadratic regulator it is known that optimal control can be used in order to obtain stabilizing feedback controllers for control systems. A generalization of this approach to nonlinear systems leads to an optimization criterion of the form

$$\underset{u\in\mathcal{U}}{\text{minimize}} \int_0^\infty \ell(x(t),u(t))dt$$

subject to

$$\dot{x}(t) = f(x(t),u(t)),\ x(0) = x_0$$

and potentially further state and/or control constraints, with $\mathcal{U}$ denoting the set of measurable control functions. Unlike the linear quadratic case, however, this nonlinear optimal control problem is in general very difficult to solve, both analytically and numerically.

In this talk we show that in addition to well known other approaches like model predictive (receding horizon) control or Zubov's method, discounted optimal control

$$\underset{u\in\mathcal{U}}{\text{minimize}} \int_0^\infty e^{-\delta t}\ell(x(t),u(t))dt$$

for sufficiently small $\delta > 0$ may also yield stabilizing controls. Since discounted optimal control problems are easier to solve than undiscounted ones (at least numerically), this simplifies the task of constructing stabilizing controls.

We present sufficient conditions, similar to those for model predictive control, which guarantee that discounted optimal trajectories are asymptotically stable at a desired equilibrium. We also discuss the effect of numerical errors when solving the discounted problem. The performance of the approach will be illustrated by a numerical example.

Economic Model Predictive Control under Bounded Disturbances

Florian A. Bayer, Frank Allgöwer
Institute for Systems Theory and Automatic Control,
University of Stuttgart

In the last years, *economic model predictive control* did arise as a new approach in the field of model predictive control (MPC). In economic MPC, more general cost functions can be considered, especially functions which are related to the "economic" performance of the system, e.g., maximizing the profit of a plant or minimizing the used energy – hence the name. This induces that the stage cost may not be positive definite with respect to a given set point. This is in contrast to the well known concept of stabilizing MPC, where a desired steady-state is tracked by employing a cost function which is positive definite with respect to this steady-state. Due to the non-definiteness, the optimal closed-loop behavior is not necessarily convergent but can be cyclic or even chaotic. Stability, if desired, can in general not be derived by the usual definiteness condition of the cost but is usually depending on the notion of dissipativity (see, e.g., [1]).

A difficulty in many practical applications of both stabilizing and economic MPC are disturbances. In previous publications in the field of robust economic MPC, the general idea was to design the MPC controller with respect to the undisturbed system and to track the resulting nominal closed-loop behavior with approaches from robust MPC. However, as the disturbances can directly affect the closed-loop performance of the system (in a negative as well as in a beneficial way), taking the influence of the disturbances into consideration within the design of the control input seems to be essential when working in the described "economic" framework. In this talk, we provide an introduction to and an overview of an approach for robust economic MPC where the influence of the disturbances is explicitly taken into account within the optimization. We propose to employ a specifically modified cost function which is based on an integration over all possible disturbances and can thus be seen as an averaging (see [2]). By using this specific cost function and suitable tube-based methods from robust MPC, reasonable approximations of the influence of the disturbance onto the behavior of the closed-loop system are given for the considered nonlinear discrete-time systems under bounded disturbances. Not only can recursive feasibility be guaranteed, but also bounds on the closed-loop average performance can be derived. In addition, stability as well as optimal operation regimes will be discussed. These can be guaranteed by the system property of dissipativity for the nominal closed-loop system. However, we will indicate that for some specific setups additional constraints are needed to enforce this dissipative behavior. We will show for some examples how taking the disturbances into account within the open-loop optimization results in a better average closed-loop performance.

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Approximate linear programming for optimal control design: a solution based on function approximation and randomization

Alessandro Falsone and Maria Prandini
Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Italy
{alessandro.falsone,maria.prandini}@polimi.it

The goal of this work is developing computationally effective control design methods for large scale systems where continuous dynamics, discrete dynamics, and uncertainty are tightly coupled, [1]. We adopt the quite comprehensive modeling framework of Markov Decision Processes (MDPs) with a hybrid (i.e. with both a continuous and a discrete component) state space, and explore the joint use of function approximation and randomized methods to defeat the curse of dimensionality, which hampers the use of standard control design techniques.

We focus on the problem of designing a state feedback control policy that maximizes an average infinite-horizon discounted reward function for an MDP with a hybrid state space and a discrete input space. The considered stochastic optimal control problem can be solved –in principle– through dynamic programming by determining the fixed-point of the Bellman equation so as to determine the so-called optimal value function and then the optimal control policy (see e.g. [2]). The optimal value function and policy can be efficiently computed when the state and control spaces are finite and not too large compared with the memory storage capacity. If the state space has a continuous component of small dimension, computations can be performed by gridding the space, approximating the original MDP with a finite state MDP, and determining the (approximate) optimal value function and control policy on the grid points. As a result, the practical use of dynamic programming is limited by the exponential growth with the problem dimensions of the computation and storage requirements.

Inspired by [3] and [4], we develop an approximate dynamic programming method resorting to random sampling of the state space instead of gridding in order to overcome these limits and avoid that complexity scales exponentially with the state space dimension.

As in [5] dealing with finite state MDP, we start by rephrasing the Bellman equation as a constrained Linear Program (LP) where the unknown quantity to be determined via optimization is the optimal value function, and it is subject to a set of constraints, one per each state-control input admissible value. When the state space has a continuous component, the resulting LP is infinite dimensional in both the decision variables and the constraints. By expressing the optimal value function to be determined as a linear combination of a finite number of basis functions, then, the infinite LP is transformed into a semi-infinite LP, i.e., an LP with finite decision variables but infinite constraints, which, in turn, can be tackled via the so-called *scenario approach* to robust convex optimization, [6, 7]. The idea of the scenario approach is to consider a finite number N of constraints only, by extracting at random N state-input pairs, and to solve the resulting finite LP. If N is appropriately chosen, then, the originally infinite constraints are guaranteed to be satisfied probabilistically, with a certain confidence. Quality of the obtained approximation of the value function (and, hence, of the resulting policy) is strongly affected by the choice of the basis functions. This is indeed a key issue in function approximation as well, where data samples in the form of input and output of an unknown (static) function are available and an approximation of the function through a linear combination of basis functions is looked for. Families of universal approximators have been studied in this contest (see e.g. [8, 9, 10]), but an effective method to select a finite number of functions out of a given family is still to be developed. The present paper represents a first step in this direction within the more challenging contest of approximate dynamic programming, the additional challenge being that input/output data samples are not available for the unknown optimal value function.

An iterative randomized scheme is proposed to compute an approximate solution to the infinite LP reformulation of Bellman equation. At each iteration, the basis functions are given and the resulting semi-infinite LP can be solved via constraint sampling. Through the iterations, the number of basis functions is increased by adding a suitably chosen basis function at each iteration. The iterative procedure is halted when some performance goal is reached or some upper bound on the number of basis functions is hit.

From an implementation point of view, the solution to each scenario LP involves integral calculations, which may hamper the computational efficiency of the method. However, in certain cases, depending on the stochastic kernel governing the MDP evolution and the chosen basis functions, integrals admit an analytic solution, which makes the overall approach particularly appealing. The approach is tested on a multi-room heating benchmark example.

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Multi-objective optimal control of fluid mixing

Sina Ober-Blöbaum, Kathrin Padberg-Gehle
Mathematics Institute, Freie Universität Berlin
Department of Mathematics, Technische Universität Dresden

Different aspects of controlling transport and mixing in fluid flows have received considerable scientific interest in the last few years. One particular focus is on controlling the evolution of advected density fields in a manner that is optimal for a predefined objective, for example such that a maximal degree of mixedness is achieved, or such that a given target density is reached as good as possible. However, many applications require the optimization of not only one but several conflicting objectives at the same time leading to *multiobjective optimal control problems*.

In this contribution we present a multi-objective optimal control framework for the optimization of advective processes with respect to certain transport or mixing properties.

Our work is based on the problem of the optimal control of mixing in Stokes fluid flow presented in [1], where a passive material is advected by the flow. To derive the underlying differential equation, we assume that the velocity field $\mathbf{u}(\mathbf{x}, t)$ is induced by a fine set of force fields $\mathbf{F}(\mathbf{x}, t) = \sum_{i=1}^{n} \alpha_i(t)\mathbf{F}_i(\mathbf{x})$, which can be modulated arbitrarily with time. Then $\mathbf{u}$ can be represented as

$$\mathbf{u}(\mathbf{x}, t) = \sum_{i_1}^{n} \alpha_i(t)\mathbf{u}_i(\mathbf{x}), \tag{1}$$

where $\mathbf{u}_i$ is the velocity field induced by the force field $\mathbf{F}_i$. The advection of a density field $c(\mathbf{x}, t)$ by the velocity field (1) is then described by

$$c_t(\mathbf{x}, t) = -\mathbf{u}(\mathbf{x}, t) \cdot \nabla c(\mathbf{x}, t) = -\sum_{i_1}^{n} \alpha_i(t)\mathbf{u}_i(\mathbf{x}) \cdot \nabla c(\mathbf{x}, t), \quad c(\mathbf{x}, 0) = c_0(\mathbf{x}). \tag{2}$$

Here, $\mathbf{c}(\cdot, t)$ is the state and $\alpha(t)$ is the control input of the control system (2).

Whereas in [1] the modulation of the force fields is searched for that achieves the best mixing for a fixed value of the action (which is the time integral of the kinetic energy per unit mass of the fluid body), in this contribution, we are interested in determining the time-dependent control α such that best mixing with minimal action is achieved. This is an multi-objective optimal control problem with the two conflicting objectives *maximal degree of mixedness*, which is quantified in terms of a mix-variance described in [1], and *minimal action*.

For the solution of such a multi-objective optimal control problem, the set of optimal compromises, the so-called *Pareto set*, has to be determined. To numerically approximate the Pareto set we combine numerical optimal control methods with reference point techniques described in [2]. By choosing appropriate reference points in the objective space, the multi-objective optimal control problem is replaced by a sequence of distance minimizing optimal control problems whose solutions are known to be points of the Pareto set. For each optimal control problem we derive the adjoint systems that provide first-order necessary optimality conditions. An adjoint based optimization together with a gradient descent method is used to solve the single-valued optimal control problems such that the Pareto set is approximated successively.

We demonstrate the flexibility of the methodology in a number of example systems, which may serve as simple models of microfluidic devices.

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An optimal junction solver for traffic flow

F. Ancona[1], A. Cesaroni[1], G.M. Coclite[2], Mauro Garavello[3]
[1]University of Padova
[2]University of Bari
[3]University of Milano Bicocca

We consider a junction composed by m incoming roads (modeled by the real interval $I_i = (-\infty, 0)$) and n outgoing ones (modeled by the real interval $I_i = (0, +\infty)$). On each road I_i we consider the Lighthill-Whitham-Richards model for traffic

$$\partial_t u_i + \partial_x f(u_i) = 0 \tag{1}$$

where $u_i = u_i(t, x)$ denotes the density of traffic at time t and position x in the i-th road I_i and $f : \mathbb{R} \to \mathbb{R}$ is the flux. Given an initial datum $\bar{u}_i$ on each road, we consider the Cauchy problem at the junction

$$\begin{cases} \partial_t u_1 + \partial_x f(u_1) = 0 & x \in I_1,\ t > 0 \\ \quad\vdots & \\ \partial_t u_{n+m} + \partial_x f(u_{n+m}) = 0 & x \in I_{n+m},\ t > 0 \\ u_1(0, x) = \bar{u}_1(x) & x \in I_1 \\ \quad\vdots & \\ u_{n+m}(0, x) = \bar{u}_{n+m}(x) & x \in I_{n+m}. \end{cases} \tag{2}$$

We address our attention to an optimal control problem for system (2). More precisely, given $T > 0$ and a function $\mathcal{J} : \mathbb{R}^m \to \mathbb{R}$, we want to select a solution to (2) which maximizes the functional

$$\int_0^T \mathcal{J}\left(f(u_1(t, 0)), \ldots, f(u_m(t, 0))\right) dt \tag{3}$$

and which respects additional constraints describing the preferences of drivers. The functional (3) depends on the traces of the fluxes of the solution to (2) at the junction.

We show that, under suitable assumptions, this maximization problem admits solutions. In general there are infinitely many solutions to the Cauchy problem (2), which maximize (3). Moreover we present some additional criteria in order to select an optimal solution.

Vanishing dielectric constant regime for the Navier Stokes Maxwell equations

Donatella Donatelli, Stefano Spirito
University of L'Aquila
GSSI - Gran Sasso Science Institute

In this talk the limit of vanishing electric permittivity in the context of Magnetohydrodynamic (MHD) equations is discussed. The classical MHD equations model the evolution of the velocity and the magnetic field in a plasma fluid. The equations are derived from the Navier-Stokes equations and the Maxwell equations by using the classical continuos mechanics theory. In particular, since in a typical conductor the characteristic velocity is much smaller than the velocity of the light the displacement of the current in the Maxwell equations is usually neglected. When one does not make this assumption in the place of the MHD equations the so called Navier-Stokes-Maxwell system are obtained. In this talk we discuss how to recover in a rigorous way the classical MHD equations from the Navier-Stokes-Maxwell system in the limit of small electric permittivity.

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Schaeffer's regularity theorem and the case of systems

L. Caravenna, L. V. Spinolo
Dipartimento di Matematica, Università di Padova
IMATI-CNR Pavia

Several regularity results hold for the Cauchy problem involving one scalar conservation law having convex flux. Among these, Schaeffer's theorem guarantees that for smooth initial data which are generic, in the Baire sense, the entropy admissible solution develops at most finitely many shocks, locally, and stays smooth out of them. My talk will focus on showing that Schaeffer's regularity result cannot be extended to strictly hyperbolic systems of conservation laws, in one space variable, satisfying the assumption analogous to the convexity of a single equation (genuinely nonlinearity): there is a set of initial data which is open in the Schwartz space and which give rise to countably many shock discontinuities, locally in space-time. This suggests that the SBV-regularity is the suitable notion of regularity for $1d$-systems of conservation laws.

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Minimal data rates and entropy in digitally networked systems

Christoph Kawan
University of Passau
Faculty of Computer Science and Mathematics

In digitally networked control systems the assumption of classical control theory that information within feedback loops can be transmitted instantaneously, lossless and with arbitrary precision is violated. This raises the question about the smallest data rate above which a given control task can be solved. For the problem to render a subset Q of the state space invariant, the minimal data rate can be described by means of an entropy-like quantity, the so-called invariance entropy (cf. [1, 4]). If one considers a single feedback loop and assumes that the system is completely controllable and uniformly hyperbolic on Q, the invariance entropy can be expressed in terms of Lyapunov exponents (cf. [2]). Furthermore, one can show that there are no cheaper strategies (i.e., such with smaller data rates) to solve the problem than by stabilization at periodic trajectories within Q. The proof of this result combines techniques from the hyperbolic theory of dynamical systems with methods from nonlinear control theory. For networks with several subsystems, which can all communicate with each other, there are different possibilities to formulate the question about the smallest data rate for the invariance problem, but also in this setting entropy-like quantities can be introduced to solve the problem (cf. [3]).

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Reachable states of a quasilinear hyperbolic control system: an application to particulate processes

Alexander Zuyev
Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany

In this presentation, we consider a class of quasilinear systems governed by the following differential equations

$$\frac{\partial}{\partial t} w(x,t) + \frac{\partial}{\partial x} F(w(x,t)) = 0, \quad x \in (0,l),\ t \geq 0, \tag{1}$$

where $w(x,t) = \big(w_1(x,t), w_2(x,t), ..., w_n(x,t)\big)^T \in \mathbb{R}^n$ describes the state of the system at a point x and time t, and the flux $F : \mathbb{R}^n \to \mathbb{R}^n$ is assumed to be of class C^1. System (1) describes a mathematical model of a moving bed chromatographic process by using the material balance of the solutes in both liquid and solid phases. The goal of this work is to study the reachable sets for such a model by using the volumetric flow rate ratio of both phases and concentrations at the inlet of the column as control parameters u. The importance of this investigation is underpinned by the practical requirement to estimate the quality of separation depending on parameters of the operating envelope of a chromatographic process.

To study the steering problem and estimate the set of reachable states, we represent system (1) with boundary controls as an abstract differential equation in a suitable Hilbert space H:

$$\frac{d}{dt}\xi(t) = A\xi(t) + \Phi\xi(t) + Bu, \quad \xi(t) \in H,\ u \in \mathbb{R}^m. \tag{2}$$

We assume that $A : D(A) \to H$ is the infinitesimal generator of a C_0-semigroup of bounded linear operators $\{e^{tA}\}_{t\geq 0}$ on H, and that the nonlinear operator $\Phi : H \to H$ satisfies the Lipschitz condition. In addition to control system (2), we also consider its linear approximation:

$$\frac{d}{dt}\xi(t) = A\xi(t) + Bu, \quad \xi(t) \in H,\ u \in \mathbb{R}^m. \tag{3}$$

The reachable sets of system (3) may be estimated by using the approach described in the book [1].

Theorem 1 [1, p. 98] *Let $\{Q_N\}_{N=1}^{\infty}$ be a family of bounded linear operators on H such that e^{tA} and Q_N commute, and let*

$$\lim_{N\to\infty} \|Q_N \xi\| = 0 \quad \text{for all}\ \xi \in H. \tag{4}$$

Assume that, for $\xi^0, \xi^1 \in H$ and any $N \geq 1$, there is a control $u^N \in L^2(0,\tau)$ such that

$$P_N\Big(\xi(\tau;\xi^0,u^N) - \xi^1\Big) = 0,\ P_N = I - Q_N, \tag{5}$$

and

$$\lim_{N\to\infty} \big(\|Q_N B\| \cdot \|u^N\|_{L^2(0,\tau)}\big) = 0. \tag{6}$$

Then, for any $\varepsilon > 0$, there exists an $N_0(\varepsilon)$ such that

$$\|\xi(\tau;\xi^0,u^N) - \xi^1\| < \varepsilon \quad \text{for each}\ N \geq N_0(\varepsilon).$$

Here $\xi(t;\xi^0,u)$ denotes the mild solution of system (3) with the initial data $\xi|_{t=0} = \xi^0 \in H$ and control $u \in L^2(0,\tau)$.

In this work, we extend Theorem 1 for the case of quasilinear control systems. By exploiting this extension, we derive sufficient controllability conditions and construct a family of open-loop controls that solves the steering problem for system (2).

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Automated generation of a dynamic feedforward control law using local model networks with disturbance inputs

Nikolaus Euler-Rolle, Christoph Hametner, Stefan Jakubek
Christian Doppler Laboratory for Model Based Calibration Methodologies at the Institute of Mechanics and Mechatronics, Vienna University of Technology

An approach is presented, which automatically generates a dynamic feedforward control law for nonlinear dynamic systems represented by discrete-time local model networks (LMN). By exploiting the generic model structure of LMN, a feedback linearizing input transformation, which subsequently is used to dynamically feedforward control the nonlinear process efficiently, can be found in a general and automated way from the data-driven dynamic process model directly. This model is represented by an LMN (e.g. [1]), which is a well-established multiple-model approach for data-driven modelling of nonlinear systems. As an interpolation between different local models, each valid in a certain operating regime, the LMN offers a versatile structure for the identification of nonlinear dynamic systems. Each operating regime represents a simple model, e.g. a linear regression model [2], whose parameters are found by identification.

When control tasks are considered, nonlinear model structures such as LMN can also be used to determine control laws and their parameters, e.g. [3]. This contribution proposes and discusses such an approach for the class of LMN where no internal dynamics are involved, i.e. the LMN has full relative degree with respect to the control signal input. Although the complexity of LMN increases with the amount of local linear models to form a sophisticated nonlinear model, the model structure still remains generic. This fact can be beneficially exploited in the application of feedback linearization (e.g. [4]) to this structure. Basically, a nonlinear system is linearized exactly by using a nonlinear coordinate transformation such that the resulting transformed system consists of an input transformation, linear external dynamics and unobservable internal dynamics. To determine the required feedforward input signal for the desired reference trajectory, the input transformation is utilized. In addition, several disturbance inputs are considered in the feedforward control law without restrictions on their relative degree. This is a common situation when control tasks are tackled which involve one controlled input and various known disturbances or inputs not used for control.

Occasionally, the required time and resources for a detailed physical modelling of a sophisticated nonlinear process are not available. In such a situation, data-driven modelling can deploy its full potential as merely input-output data are required to obtain a dynamic process model. Hence, the proposed approach supersedes the need for an in-depth knowledge of the underlying nonlinear process as the generic model structure of LMN allows for an automated generation of a feedforward control law. Both, LMN and the concept of feedback linearization are by themselves well established concepts in academia as well as in the industry. However, combining both ideas offers the opportunity to provide a substantial tool to dynamically feedforward control any arbitrary nonlinear process with measureable disturbances and with knowledge of measured input-output data only. The application of the proposed approach to the airpath of a diesel engine, where the intake manifold pressure is controlled by a variable-geometry turbocharger, yields good tracking performance.

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Structure-preserving discrete-time LQR problems

Kathrin Flaßkamp, Todd D. Murphey
Northwestern University, USA

The optimal solution of a linear quadratic regulator (LQR) problem in continuous time, i.e. the state and adjoint trajectories, solves a linear Hamiltonian two-point boundary value problem. Often, the optimal solution is determined by the corresponding Riccati matrix differential equation. When approximating the true solution by numerical integration, it is desirable to preserve the problem's original symplectic structure given by the Hamiltonian dynamics.

We first study the discretization approach based on Euler integration, which is commonly used in control applications. As a corollary of Hager's result in [1], this leads to a discretization of the state-adjoint system by a symplectic Euler method. In the discrete-time LQR case, we link this to the well known discrete-time Riccati equations. In this contribution, we focus on optimal control of mechanical systems, for which the symplectic structure due to Hamiltonian dynamics can be preserved by using *variational integrator* discretizations (cf. [2]), also known as *discrete mechanics* models. Using a result from [3], we complement the symplectic state discretization with a discrete adjoint scheme to obtain a symplectic state-adjoint scheme. Then we derive modified discrete-time Riccati equations.

The symplectic discretization of the Hamiltonian state-adjoint system allows for backward error analysis (cf. [2]). In particular, the existence of a *modified Hamiltonian* of the optimal control problem is guaranteed. Applications of discrete-time LQR control go beyond linear systems, as, for instance, projection-based optimization methods for nonlinear systems use local linearizations and subsequently solve linear quadratic problems (cf. [4]).

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Reconstruction of independent sub-domains for a class of Hamilton-Jacobi equations and application to parallel computing

Adriano Festa,
RICAM - Johann Radon Institute
for Computational and Applied Mathematics
Austrian Academy of Sciences

A previous knowledge of the domains of dependence of a Hamilton-Jacobi equation can be useful in its study and approximation. Information of this nature is, in general, difficult to obtain directly from the data of the problem. In this talk we introduce formally the concept of *independent sub-domain* discussing its main properties and we provide a constructive implicit representation formula. Using such results we propose an algorithm for the approximation of these sets that is shown to be relevant in the numerical resolution via parallel computing.

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