NONLINEAR CONTROL NETWORK

3rd NCN WORKSHOP

»Dynamics, Bifurcations and Control«

Kloster Irsee, Germany

April 1−3, 2001

Final Program

and

Book of Abstracts

NCN web site: www.supelec.fr/lss/NCN

Morning Program

Time	Sunday	Monday	Time	Tuesday
8:50–9:00	**Welcome Address**			
9:00–9:50	**A. Krener** Control Bifurcations	**E. Abed** Monitoring and Control of Bifurcations Using Probe Signals	9:00–9:50	**P. Soravia** Stability of Control Systems Affected by Disturbances: The Role of Differential Games
9:50–10:10	**A. Ilchmann** Dynamics of Adaptive Control Systems	**A. Barreiro–Blas, A. Baños, F. Gordillo, J. Aracil** Nonlinear Problems im Simple Electromechanical Systems	9:50–10:10	**H. Crauel** Noise Assisted Stabilization
10:10–10:30	**D.M. Alonso, E. Paolini, J.L. Moiola** Controlling an Inverted Pendulum with Bounded Control	**S. Hecker, J. Mareczeck** Dynamic Invariance Control for a Class of Nonlinear Underactuated Systems	10:10–10:30	**C. Schweiger, J. Mareczeck** Robust Switching Control of an Underactuated Robot Experiment
Coffee				
11:00–11:50	**W. Kang** Normal Form, Invariants, and Bifurcations of Nonlinear Control Systems	**A. Tesi** Bifurcations of Neural Networks with Almost Symmetric Interconnection Matrices	11:00–11:20	**A. Pisano, G. Bartolini, S. Pillosu** Closed–Loop Time–Optimal Stabilization of a Third–Order Integrator
11:50–12:10	**W. Respondek, I.A. Tall** Canonical Forms and Symmetries of Single–Input Nonlinear Control Systems	**V.M. Vega** Some Remarks on Walking Robots, Symmetries and Bifurcations	11:20–11:40	**A. Bacciotti, F. Ceragioli** Optimal Regulation and Damping Feedback
12:10–12:30	**I.A. Tall, W. Respondek** Feedforward Forms of Single–Input Systems	**F. Gordillo, I. Alcalá, J. Avacil** Bifurcations in Systems with a Rate Limiter	11:40–12:00	**D.F.M. Torres** Conservation Laws in Optimal Control
12:45	**Lunch**		12:00–12:20	**R. Sepulchre, F. Grognard, J. De Dona** A Dynamical System that Computes Time–Optimal Switchings for Bang-Bang Control of Linear Systems
			12:20–12:30	**Closing Remarks**
			12:30	**Lunch**

Afternoon Program

Time	**Sunday**	**Monday**
14:30–15:20	**C. Byrnes** Towards a Nonequilibrium Theory for Nonlinear Control Systems	**W. Kliemann** Bifurcation of Control Flows
15:20–15:40	**C. Piccardi** Reduced Models for Systems with Low–Dimensional Chaos	**D. Szolnoki** Computation of Control Sets using Subdivision and Continuation Techniques
15:40–16:00	**J.L. Gallardo** On Constrained Dynamical Systems and Algebroids	**L. Giovanardi, M. Basso** Stability Analysis of Periodic Solutions via IQC
	Coffee	
16:30–17:10	**R. Johnson** The Frequency Theorem for Nonperiodic Systems	**F. Wirth** Stability of Linear Inclusions and Local Robustness of Nonlinear Systems
17:10–17:30	**J.C. Raimùndez** Hamiltonian Controller Synthesis Using Evolutive Strategies	**M. Spadini** A Dynamic Index for Control Systems
17:30–17:50	**F.M. Atay** Hopf Bifurcation and Oscillation Control in Delayed Feedback Systems	**Q. Zhang, B. Delyon** Design of MIMO Adaptive Observers with Exponential Convergence
17:50–18:10	**E. Trélat** Optimality of Singular Trajectories and Asymptotics of Accessibility Sets	**D. Arotaritei, I. Grosu** A New Nonlinear Control: The Open–Plus–Closed–Loop (OPCL)–Method
18:30		**Guided Tour through Irsee's local brewery**
19:00	**Dinner**	
19:30		**Dinner**
20:00	**Guided Tour through Kloster Irsee**	

Abstracts

Sunday, 9:00

A. Krener
University of California, Davis, CA, USA

Control Bifurcations

A classical bifurcation of a parametrized ordinary differential equation typically occurs when some eigenvalues of the linear approximations cross the imaginary axis and there is a loss of stability. A bifurcation of a control system typically occurs when there is a loss of stabilizability. We examine the simplest cases where this occurs (Joint work with W. Kang and D.-E. Chang).

Sunday, 9:50

A. Ilchmann
TU Ilmenau, Germany

Dynamics of Adaptive Control Systems

We introduce a simple proportional output controller with adaptive high-gain parameter. The controller achieves prescribed practical tracking of bounded reference signals with bounded derivative if applied to a class of controlled dynamical systems modelled by functional differential equations. This class encompasses systems with hysteresis, delays and distribution effects. Limitations of the adaptive controller are shown when a so called sigma-modification is incorporated. In this case we can already show for two dimensional linear systems a rich scenario of bifurcation phenomena.

Sunday, 10:10

D.M. Alonso, E. Paolini, J.L. Moiola
Universidad Nacional del Sur, Bahia Blanca, Argentina
(J.L. Moiola: currently at Universität zu Köln, Germany)

Controlling an Inverted Pendulum with Bounded Controls

In this paper we analyze the dynamical behaviour of a simple underactuated mechanical system subject to bounded controls. The system consists of a pendulum with an inertia disk mounted on its free extreme. The pendulum‘s arm is not actuated, and the only way to move it is by applying a torque to the inertia disk by means of a DC motor. We show that even with bounded controls, the inverted (unstable) position can be reached if the controller‘s gains are appropriately chosen. However, a rich and complex dynamics can be obtained for other gains values, for example the presence of stable and unstable limit cycles collapsing in a fold bifurcation is shown.

Sunday, 11:00

W. Kang

Naval Postgraduate School, Monterey, CA, USA

Normal Form, Invariants, and Bifurcations of Nonlinear Control Systems

It is a review of bifurcation theory for control systems in normal form. Two related problems, namely the bifurcation of control systems and the feedback control of bifurcations, will be introduced. Normal forms and invariants of nonlinear control systems under the transformation group of homogenous feedback and change of coordinates will be explained. For systems with one or two uncontrollable modes, the relationship between the invariants and the system's qualitative behavior is introduced. Other topics and concepts include the manifold of equilibrium, the controllability and stabilizability at a bifurcation point, and the stability of periodic solutions. Examples will be shown to illustrate the theory and its applications.

Sunday, 11:50

W. Respondek, I.A. Tall

INSA Rouen, France

Canonical Forms and Symmetries of Single-Input Nonlinear Control Systems

In the first part of the talk we will recall a recently obtained canonical forms for single-input nonlinear systems, which complete a theory of normal forms developed by Kang and Krener. Then we show how our canonical forms allow to prove the following surprising result: any single input system that is not linearizable and whose first order approximation is controllable does not admit any stationary symmetry (except for a small class of odd systems which we completely characterize). Finally, we will discuss—still using our canonical forms—arbitrary (not necessarily stationary) symmetries of single-input systems.

Sunday, 12:10

I.A. Tall and W. Respondek

INSA Rouen, France

Feedforward Forms of Single–Input Systems

Recently there has been a growing interest in various feedforward forms for nonlinear systems, mainly because of their application to stabilizability. We will argue that a theory of normal forms developed by Kang and Krener, and completed recently by us, provides useful tools to analyse such systems. We will present a step–by–step procedure which allows to bring, in a constructive way, any given system, for which it is possible, to strict feedforward form. Then we will discuss modifications of our normal forms, our conditions, and of our construction in the case of (non strict) feedforward and dual feedforward forms.

Sunday, 14:30

C. Byrnes

Washington University, St. Louis, MO, USA

Towards a Nonequilibrium Theory for Nonlinear Control Systems

Sunday, 15:20

C. Piccardi

Politecnico di Milano, Italy

Reduced Models for Systems with Low–Dimensional Chaos

A reduced (approximate) model, namely a hybrid system composed by the feedback connection of a one–dimensional map and a finite–state automaton, can often be associated to dynamical systems (ODEs) with a low–dimensional chaotic attractor. This simplified modeling allows one to efficiently solve problems such as control and short–term prediction. The talk, with the help of some popular chaotic systems, will discuss several issues related to the identification of the reduced model and to its use in control design. Other related issues, e.g. the extension of the approach to some infinite–dimensional systems and the identification of the reduced model from noisy data, will also be considered.

Sunday, 15:40

J.L. Gallardo

University of Twente, The Netherlands

On Constrained Dynamical Systems and Algebroids

In 1994, van der Schaft and Maschke defined a(n) (almost) Poisson structure for the study of constrained port controlled Hamiltonian systems as systems obtained by reduction. This note intends to provide a geometrical framework that justifies such construction, based on the use of Lie algebroids.

Sunday, 16:30

R. Johnson

Università di Firenze, Italy

The Frequency Theorem for Nonperiodic Systems

In 1986 V.A. Yakubovich published a paper discussing a non-definite linear-quadratic optimisation problem and the Frequency Theorem for the periodic Lurè equation. In joint work with R. Fabbri and C. Nunez some of his results are extended to general non-autonomous problems. The key concepts used are those of exponential dichotomy and rotation number for linear Hamiltonian systems.

Sunday, 17:10

J.C. Raimùndez

Universidad de Vigo, Spain

Hamiltonian Controller Synthesis Using Evolutive Strategies

The presentation focuses on Hamiltonian Controller Synthesis using the Evolutive Strategies unsupervised learning capabilities, issued from their evolutionist paradigm. The controller synthesis problem is reduced to a minimization problem over a parametric space. The training process intends to construct a matrix couple (J,R). Those matrices and the needed energy correction assures local asymptotic stability on the port controlled plant.

Sunday, 17:30

F.M. Atay

Artesis A.S., Tuzla, Istanbul, Turkey

Hopf Bifurcation and Oscillation Control in Delayed Feedback Systems

The control of limit cycle oscillations is discussed for nonlinear delayed feedback systems. Through a center manifold reduction, the effects of the control parameters are determined on the Hopf bifurcation that gives rise to periodic behavior. The results are applied to the perturbed harmonic oscillator under the action of delayed feedback of position, which is a prototype system commonly arising in diverse biological and industrial settings. It is shown that linear feedback can annihilate limit cycles and stabilize the origin. Furthermore, using a cubic feedback function, an asymptotically stable limit cycle can be created oscillating at an arbitrary prescribed amplitude.

Sunday, 17:50

E. Trélat

Université de Bourgogne, Dijon, France

Optimality of Singular Trajectories and Asymptotics of Accessibility Sets

We investigate minimization problems along a singular trajectory of a single–input affine control system with constraint on the control, and then as an application of a sub–Riemannian system of rank 2. Under generic assumptions we get necessary and sufficient conditions for optimality of such a singular trajectory. Moreover we describe precisely the contact of the accessibility sets at time T with the singular direction. As a consequence we obtain in sub–Riemannian geometry a new splitting–up of the sphere near an abnormal minimizer γ into two sectors, bordered by the first Pontryagin's cone along γ, called the L_∞–sector, and the L_2–sector.

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[2] A. Agrachev, A.V. Sarychev, Abnormal sub-Riemannian geodesics: Morse index and rigidity,

Annales del'IHP, 1996, Vol. 13, 635–690.
[3] A. Agrachev, A.V. Sarychev, On abnormal extremals for Lagrange variational problems, J. of Math. Systems, Estimation, and Control, Vol. 8, No. 1, 1998, 87–118.
[4] B. Bonnard, I. Kupka, Théorie des singularités de l'application entrée/sortie et optimalité des trajectories singulières dans le problème du temps minimal, Forum Math. 5 (1993), 111–159.
[5] M.R. Hestenes, Applications of the theory of quadratic forms in Hilbert space to the calculus of variations, Pacific J. Math., 1951, Vol. 1, 525–581.
[6] A.V. Sarychev, The index of the second variation of a control system, Math. USSR Sbornik, 1982, Vol 41, No. 3.

Monday, 9:00

E. Abed
University of Maryland, USA

Monitoring and Control of Bifurcations Using Probe Signals

Bifurcation control involves modifying the bifurcation behavior of a nonlinear system, usually to mitigate undesirable effects associated with subcritical (or hard) bifurcations. A main reason for the need for bifurcation control designs is model uncertainty. Because of model uncertainty, off–line calculations of a safe operating envelope of a nonlinear system are subject to error. Exceeding the safe operating envelope even slightly leads to instability and the associated bifurcations. Thus, bifurcation control was investigated in order to manage system behavior at and past the boundary of its stable operating range. In this talk, closed–loop monitoring systems for detecting impending instability in nonlinear uncertain systems are described. The monitoring systems are shown to facilitate detection of proximity to static or oscillatory instability prior to the actual initiation of instability. Moreover, the monitoring systems can be designed to mitigate the severity of bifurcations and to distinguish subcritical bifurcations from supercritical bifurcations before the bifurcations occur. The work makes use of probe signals, such as noise or periodic excitation, for system monitoring.

Monday, 9:50

A. Barreiro–Blas, A. Baños, F. Gordillo, J. Aracil
Universidad de Vigo and Universidad de Sevilla, Spain

Nonlinear Problems in Simple Electromechanical Systems

In this work, simple electromechanical systems are considered. The objective is to show that these very simple systems may present complex global behaviors and induce complex problems of controller synthesis. This will be addressed by using complementary nonlinear approaches. Conic analysis will provide tools for characterization of robust stability for conic bounded nonlinearities of two types: time-varying gains and dynamical uncertainty. Qualitative theory and bifurcation analysis can help to gain understanding and intuition about the possible causes for the loss of stability and about the complex shape of the attraction basin. They can be useful in reducing the conservatism of the conic analysis.

Quantitative feedback theory (QFT) provides tools for integrating, in a frequencial setting, stability conditions from the two previous approaches, as well as other performance objectives.

Monday, 10:10

S. Hecker, J. Mareczek
TU München, Germany

Dynamic Invariance Control for a Class of Nonlinear Underactuated Systems

In this paper we consider asymptotic stabilization of SISO–Systems consisting of a linear double integrator subsystem and input driven internal dynamics which can be unstable. Static Invariance Control achieves stabilization to equilibrium manifolds by keeping a bounded state space region invariant, while maintaining asymptotic stability of the linear subsystem by a switching control. This method is extended to Dynamic Invariance Control, yielding asymptotic stability of the overall system. The proposed theory is validated with an underactuated 2–DOF SCARA–type robot.

Monday, 11:00

A. Tesi
Università di Firenze, Italy

Bifurcations of Neural Networks with Almost Symmetric Interconnection Matrices

It is well known that symmetric neural networks are completely stable, i.e., each trajectory converges towards some equilibrium point [1]–[2]. However, in any practical neural networks realization it is not possible to obtain perfect symmetric neuron interconnections, since this would require the exact equality between pairs of physically distinct components. Therefore, robustness of complete stability with respect to small perturbations of the nominal symmetric neuron interconnection is a quite important issue [3]–[4]. In this talk, this robustness issue is investigated in some detail. In particular, it is shown that non–convergent dynamics can be found even arbitrarily close to the nominal case of symmetric interconnection matrices. Said another way, this shows that the symmetry of the interconnection matrix alone, is not sufficient to guarantee robustness of complete stability in the general case. More specifically, some basic neural networks configurations are discussed, showing that it is possible to analytically prove the existence of stable limit cycles as close as one pleases to symmetry. These limit cycles can be originated by local Hopf–like bifurcations of an equilibrium point, or by global heteroclinic bifurcations. Moreover, numerical simulations make it evident the possible occurrence of more complex bifurcations close to symmetry, such as period–doubling bifurcations, which can lead to the birth of complicated chaotic–like attractors.

[1] M. Hirsch, Convergent activation dynamics in continuous time networks, Neural Networks, vol. 2, pp. 331-349, 1989.

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[3] M. Vidyasagar, Location and stability of the high-gain equilibria of nonlinear neural networks, IEEE Trans. Neural Networks, vol. 4, pp. 660-672, 1993.
[4] K. Wang and A.N. Michel, Robustness and perturbation analysis of a class of nonlinear systems with applications to neural networks, IEEE Trans. Circuits Syst. I, vol. 41, pp. 24-32, 1994.

Monday, 11:50

V.M. Vega
Ghent University, Belgium

Some Remarks on Walking Robots, Symmetries and Bifurcations

In a recent paper due to Golubitsky and his colleagues symmetry methods are used to study networks of coupled cells, with are models for central pattern generators. They study the locomotion in 2n-legged animals and conclude that their symmetry methods can properly explain the generation of primary gaits in those animals by considering a network of n coupled cells. In this contribution we make some remarks on the applicability of Golubitsky‘s results when dealing with four-legged robots.

Monday, 12:10

F. Gordillo, I. Alcalá, J. Aracil
Universidad de Sevilla, Spain

Bifurcations in Systems with a Rate Limiter

In this paper, a class of non–linear systems consisting of a unity feedback of a linear dynamical system with a rate limiter at the input, are considered. It will be shown that this kind of systems may suffer bifurcation–like behaviours such as Hopf, saddle–node at infinity and saddle–node of periodic orbits bifurcations. This analysis is carried out by using the describing function method.

Monday, 14:30

W. Kliemann
Iowa State University, Ames, IA, USA

Bifurcation of Control Flows

The notion of control flows associates a dynamical system, a skew product flow, to open loop control systems. Then concepts and methods from dynamical systems can be transferred to control systems. The insights and the research problems connected with this approach will be explained.

Monday, 15:20

D. Szolnoki

Universität Augsburg, Germany

Computation of Control Sets using Subdivision and Continuation Techniques

A key notion for the analysis of the global behaviour of control systems are control sets. Control sets are subsets of the state space where approximate controllability holds: from every point in a control set one can steer arbitrarily close to any other point in the control set. In general it is not possible to find explicit formulas for control sets and their domains of attraction. Therefore numerical methods are a natural part of a systematic analysis. We will present a method for the computation of control sets, which is based on subdivision and continuation techniques.

Monday, 15:40

L. Giovanardi, M. Basso

Università di Firenze, Italy

Stability Analysis of Periodic Solutions via IQC

We consider L_2–stability of periodic solutions for a class of periodically forced nonlinear systems depending on a scalar parameter and subject to disturbances. A preliminary result concerning local existence of a family of periodic solutions for such systems is first given. Subsequent stability analysis is based on a combined use of linearization techniques and frequency–domain stability criteria in terms of Integral Quadratic Constraints (IQC).

Monday, 16:30

F. Wirth

Universität Bremen, Germany

Stability of Linear Inclusions and Local Robustness of Nonlinear Systems

Exponential stability of linear differential or discrete inclusions is characterized by the maximal Lyapunov exponent (also named generalized spectral radius in the discrete time case). We discuss regularity properties of this quantity, namely Lipschitz continuity on the space of compact irreducible sets of matrices and a monotonicity property. These results can be applied in the local robustness analysis of nonlinear systems at singular points. We will discuss a fundamental difference between the discrete and the continuous time case, which lies in the fact that in discrete time the linearization at a singular fixed point completely describes the local robustness properties of the nonlinear system, while this is false in continuous time.

Monday, 17:10

M. Spadini

Università di Firenze, Italy

A Dynamic Index for Control Systems

We contribute to the classification of the controllability behavior of nonlinear systems by attaching an 'index' (a particular semigroup) to local control sets (i.e. locally maximal subsets of complete controllability). The proposed index 'measures' the different ways the system can go through the local control set (joint work with F. Colonius).

Monday, 17:30

Q. Zhang, B. Delyon

IRISA–INRIA, Rennes, France

Design of MIMO Adaptive Observers with Exponential Convergence

For systems of the form

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B(t)u(t) + \Psi(u, y, t)\theta + \varphi(u, y, t) \\ y(t) &= Cx(t) \end{aligned}$$

with $x \in \mathbb{R}^n$, $u \in \mathbb{R}^l$, $y \in \mathbb{R}^m$, we consider the joint state–parameter estimation, i.e., the design of adaptive observers simultaneously estimating $x(t)$ and θ. Under the detectability condition of the matrix pair (A, C) and the persistent excitation condition, we propose an adaptive observer with global and exponential convergence, naturally formulated for multi–input–multi–output (MIMO) systems. It is conceptually and computationally simple. Its potential applications are on–line continuous–time system identification, fault detection and isolation, and adaptive control of MIMO systems.

Monday, 17:50

D. Arotaritei, I. Grosu

Aalborg University, Denmark and University of Medicine and Pharmacy, Iasi, Romania

A New Nonlinear Control: The Open-Plus-Closed-Loop (OPCL)-Method

OPCL is mathematically justified [1]. It is very robust against noise [2]. It gives an analytic solution to the stabilization of the inverted pendulum [3]. Others improved, completed OPCL [4]. Efforts are needed to make it easier implementable.

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[4] J. Wang, X. Wang, Int. J. Control, 72(10), 911, 1999.

Tuesday, 9:00

P. Soravia

Università di Padova, Italy

Stability of Control Systems Affected by Disturbances: The Role of Differential Games

Stability and stabilizability of systems are classical subjects. Recently, as opposed to stochastic optimal control, increasing interest has been devoted to cases when disturbances are modelled deterministically as unknown measurable functions. Stability can then be discussed in different ways according for instance to the fact that we decide to check if an equilibrium is stable despite of the presence of noise (worst case approach) or, when disturbances may be unbounded, we want to 'measure' how a stable equilibrium in absence of disturbances is affected by noise (as in H_∞ control). For general nonlinear systems I will discuss the concept of Lyapunov function in such situations and the partial differential inequalities that they satisfy.

Tuesday, 9:50

H. Crauel

TU Ilmenau, Germany

Noise Assisted Stabilisation

We investigate proportional output feedback stabilisation of linear systems perturbed by noise. Assuming neither minimal phase nor asymptotically stable zero dynamics—hence the deterministic system cannot be stabilised—we show that the system can be stabilised provided the intensity of the noise is sufficiently large.

Tuesday, 10:10

C. Schweiger, J. Mareczek

TU München, Germany

Robust switching control of an underactuated robot experiment

In this paper a novel switching control method for a class of nonlinear non–minimum phase SISO systems with rank 2 and perturbed system parameters is proposed. The control objective is to control the output function to a constant desired value while keeping a bounded state space region robustly invariant. Therefore former results on invariance control are extended to handle the parameter perturbed case and a robust switching strategy is established. The theory is applied in experiments to an underactuated 2–DOF SCARA–type robot which can be perturbed by an additional mass.

Tuesday, 11:00

A. Pisano, G. Bartolini, S. Pillosu

Università di Cagliari, Italy

Closed–Loop Time–Optimal Stabilization of a Third–Order Integrator

We propose a closed–loop solution to the time–optimal control problem for a third–order integrator. The resulting control is discontinuous, and the proposed scheme is shown to be robust against matched disturbances. In particular, it is demonstrated that the finite–time stabilization of a class of uncertain third–order uncertain systems can be ensured by suitable choice of the control amplitude.

Tuesday, 11:20

A. Bacciotti, F. Ceragioli

Politecnico di Torino, Italy

Optimal Regulation and Damping Feedback

The relationships between the quadratic regulator problem on the infinite horizon and the stabilization problem are well understood in the case of linear systems. The two problems are actually equivalent and they are also equivalent to solvability of the Riccati equation. Analogous results for nonlinear systems have been pointed out in a particular way in the literature. Here we deal with nonlinear systems affine in the control. By means of a suitable re–interpretation of certain well known results and some new lemmas we generalize the linear scheme in a very satisfactory way in the case the value function of the optimisation problem is continuously differentiable. Some attempts in the direction of relaxing the smoothness assumption on the value function are also done.

Tuesday, 11:40

D.F.M. Torres

Universidade de Aveiro, Portugal

Conservation Laws in Optimal Control

Emmy Noethers celebrated theorem is the result of major importance for various areas of modern physics. It relates the invariance properties of an integral functional in the calculus of variations with the conservation laws, that is, with the integrals of the corresponding Euler–Lagrange differential equations. We present a generalization of E. Noethers theorem for the Pontryagin extremals of optimal control problems. The formulation involves a one–parameter family of smooth maps which may depend on the control.

Tuesday, 12:00

R. Sepulchre, F. Grognard, J. De Dona
University of Liège, Belgium

A Dynamical System that Computes Time–Optimal Switchings for Bang–Bang Control of Linear Systems

It is well known that the time–optimal control of linear systems with bounded input is generically bang–bang. In this paper, we study the case of real eigenvalues in dimension n, in which case the time–optimal solution involves at most $n - 1$ switches. We prove the convergence properties of a dynamical system the solution of which 'computes' the time–optimal sequence of switches. This algorithm can be used for a receding–horizon implementation of time–optimal control.

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