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WORKSHOP ON CONTROL OF DYNAMICAL SYSTEMS

BOOK OF ABSTRACTS








Workshop on Control of Dynamical Systems

14th–16th June 2021
Dubrovnik, Croatia

The workshop is organized within the framework of the project Control of Dynamical Systems funded by Croatian Science Foundation. Its purpose is to provide a discussion forum between the project members and their national and international collaborators. The workshop will take place at the University of Dubrovnik and will be conducted in a hybrid modality (virtual and live meetings).

Coordinator:

Martin Lazar (University of Dubrovnik, Croatia)

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9 : 45 − 10 : 15	Martin Lazar	Greedy Algorithm for Parameter Dependent Operator Lyapunov Equations. Application to Control Problems
10 : 15 − 10 : 45	Coffee Break	
10 : 45 − 11 : 30	Enrique Zuazua	Dynamics and control of a guiding model
11 : 30 − 12 : 00	Cristhian Montoya	Robust control and Stackelberg strategy for a fourth–order parabolic equation
15 : 00 − 15 : 45	Jérôme Lohéac	Some contributions to output controllability
15 : 45 − 16 : 15	Domagoj Tolic	Stabilizing Transmission Intervals and Delays in Nonlinear Networked Control Systems through Hybrid-System-with-Memory Modeling and Lyapunov-Krasovskii Arguments
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9 : 45 − 10 : 30	Andrej Jokić	Market-based power systems: a control perspective
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9 : 45 − 10 : 30	Marko Erceg	Strong traces to degenerate parabolic equations
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11 : 30 − 12 : 00	Jelena Jankov	Two-phase optimal design for elastic plate
12 : 00 − 12 : 30	Irena Vašiček	Application of homogenization to an optimal design problem

Invited talks

LQResNet: Using DNNs for Learning of Dynamical Systems

Peter Benner
Max Planck Institute for Dynamics of Complex Technical Systems, Germany

Mathematical modeling is an essential step, for example, to analyze the transient behavior of a dynamical process and to perform engineering studies such as optimization and control. With the help of first-principles and expert knowledge, a dynamic model can be built. However, for complex dynamic processes, appearing, e.g., in biology, chemical plants, neuroscience, financial markets, this often remains an onerous task. Hence, data-driven modeling of the dynamics process becomes an attractive choice and is supported by the rapid advancement in sensor and measurement technology. Data-driven methods such as Dynamic Model Decomposition (DMD) and Operator Inference (OpInf), learn models of dynamical systems from data. In this talk, we suggest combining OpInf with deep neural network (DNN) approaches to infer the unknown nonlinear dynamics of the system. The approach uses recent advancements in deep learning and prior knowledge of the process if possible. We demonstrate that the proposed methodology accomplishes the desired tasks for dynamics processes encountered in neural dynamics and the glycolytic oscillator.
This talk is based on joint work with Pawan Goyal.

Strong traces to degenerate parabolic equations

Marko Erceg
Department of Mathematics, University of Zagreb, Croatia

In this talk we study entropy solutions of degenerate (homogeneous) scalar parabolic equations and prove that all such solutions admit the strong trace at $t = 0$. No nondegeneracy conditions on the flux and the diffusion matrix are required. Here the degeneracy appears as the diffusion matrix is only positive semi-definite, i.e. it can be equal to zero in (variable-dependent) directions. Although the well-posedness for the Cauchy problems (under the strong trace) corresponding to such equations is well established in quite general situations, our result implies that the weak trace suffices for uniqueness. Moreover, this result could be an important step into formulating the initial boundary value problem in the sense of Bardos, LeRoux and Nédélec.
This is joint work with Darko Mitrović.

Rational function surrogate modeling for the optimal control of parabolic systems

Luka Grubišić
Department of Mathematics, University of Zagreb, Croatia

We consider an optimal control problem for a general linear parabolic equation governed by a self-adjoint operator on an abstract Hilbert space. The task consists in identifying a control (entering the system through the initial condition) that minimises the distance of the trajectory of the system from a given constraint while steering the final state at time T ¿ 0 close to the given target. First, we obtain the closed form solution for several types of trajectory constraints. Then second we present a numerical scheme based on the award wining rkfit algorithm for approximating the trajectory of the system using spectral calculus and a rational function surrogate.
This talk is based on joint work with Martin Lazar, Ivica Nakic and Martin Tautenhahn.

Market-based power systems: a control perspective

Andrej Jokić
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia

Over the past decades, electrical power systems have been going through some major restructuring processes. Central to these changes are a policy shift towards competitive market mechanisms for their operation and large-scale integration of intermittent, renewable power sources (wind and sun). As a consequence, these systems are characterized with decentralized decision making, large uncertainties, interconnected dynamics and large scale. The main focus of this talk is on challenges in managing complexity of such a system in the operational and control design, with an emphasis on scalability of analysis/synthesis, robustness and reliability. Several results will be presented and discussed, including distributed, real-time price-based control of power systems, provision of power balancing ancillary services and distributed algorithms for robust congestion management.

Some contributions to output controllability

Jérôme Lohéac
CNRS, CRAN, Université de Lorraine, France

In this talk we will only deal with linear time invariant and finite dimensional control systems. This notion of output controllability has been first introduced in the 60s by Bertam and Sarachik and their results have been extended some years later by Kreindler and Sarachik. More precisely, they extend the well–known necessary and sufficient conditions for (state) controllability, i.e. Kalman rank condition and positivity of the controllability Gramian, to the framework of output controllability. We will see in this talk that the Hautus test

condition can also be adapted for output controllability. In a second part of the talk, we will consider the notion of "long-time output controllability". More precisely, the question we would like to answer is: "If a desired output can be reached in some time $T > 0$, can we design a control such that this output remains constant for later times $t > T$?" We will see that necessary and sufficient conditions for long-time output controllability are the ones of output controllability for an extended system output.
These works have been made in collaboration with B. Danhane, M. Jungers and M. Lazar.

Global Controllability for Quasilinear Non–negative Definite System of ODEs and SDEs

Darko Mitrović
Faculty of Mathematics, University of Vienna, Austria

We consider a control problem for a system of quasi-linear ODEs and SDEs with a non-negative definite symmetric matrix of the system. The strategy of the proof is the standard linearization of the system by fixing the function appearing in the nonlinear part of the system, and then applying the Leray–Schauder fixed point theorem. We shall also need the continuous induction arguments to prolong the control to the final state which is a novel approach in the field. This enables us to obtain controllability for arbitrarily large initial data (so called global controllability).

Null controllability for the semigroup of the harmonic oscillator

Ivan Veselić
Fakultät für Mathematik, Technische Universität Dortmund, Germany

More than 15 years ago it was established that control on any set of positive Lebesgue measure is sufficient to drive the solution of the free heat equation on a bounded domain with Dirichlet boundary conditions to zero at any prescribed positive time. More recently, it was established that the free heat equation in the whole euclidean space is null controllable iff the sensor set is thick. In the first case the spatial domain is bounded and the generator has purely discrete spectrum. In the second case the spatial domain is unbounded and the generator has purely continuous spectrum. Our interest is to reconcile and interpolate these two phenomena. This can be done, on one hand, by a quantitative analysis of the control cost estimates and their dependence on the geometric features of the spatial domain and the sensor set. On the other hand, the control problem for the semigroup generated by the harmonic oscillator exhibits a mix of the phenomena spelled out above: The spatial domain is unbounded, but the generator has purely discrete spectrum. We present new uncertainty principles of Hermite functions that imply null controllability for sensor sets that are much sparser than thick sets.
This is joint work with A. Dicke and A. Seelmann.

Dynamics and control of a guiding model

Enrique Zuazua
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) / Alexander von Humboldt Foundation, Germany /Fundación Deusto and Universidad Autónoma de Madrid, Spain

We model, simulate and control the guiding problem for a herd of evaders under the action of repulsive drivers. The problem is formulated in an optimal control framework, where the drivers (controls) aim to guide the evaders (states) to a desired region of the Euclidean space. Classical control methods allow to build coordinated strategies so that the drivers successfully drive the evaders to the desired final destination. But the computational cost quickly becomes unfeasible when the number of interacting agents is large. We present a method that combines the Random Batch Method (RBM) and Model Predictive Control (MPC) to significantly reduce the computational cost without compromising the efficiency of the control strategy. An analysis of the comnvergence of these methods, together with some open problems will also be presented.
This talk is based on joint work with Dongnam Ko, from the Catholic University of Korea, and Daniël Veldman (FAU).

Contributed talks

Explicit Hashin-Shtrikman bounds and optimality criteria method for optimal design problems in 3D linearized elasticity

Krešimir Burazin
J. J. Strossmayer University of Osijek, Department of Mathematics

We consider optimal design problems in the setting of linearized elasticity, where the mechanical behaviour of the domain is modeled with linearized elasticity system of PDEs, and restrict ourselves to domains filled with two isotropic elastic phases. Since the classical solution usually does not exist, we use relaxation by the homogenization method in order to get a proper relaxation of the original problem. While, unfortunately, a G-closure problem is still an open problem in the context of linearized elasticity, we have on our disposal various bounds on this set. Probably the most prominent representative among them are famous Hashin-Shtrinkman bounds, which have imposed themselves as the benchmark against which most experimental results are compared. A need for explicit calculation of Hashin-Shtrikman bounds is also important for structural optimization, as these bounds prove essential for some numerical methods for optimal design problems. An explicit calculation of bounds in three space dimensions requires a rather tedious and formidable calculations, and thus, up to date, it remained an open problem.

Two-phase optimal design for elastic plate

Jelena Jankov
J. J. Strossmayer University of Osijek, Department of Mathematics

Homogenization theory is one of the most successful approaches for dealing with optimal design problems, that consists in arranging given materials such that obtained body satisfies some optimality criteria, which is mathematically usually expressed as minimization of some (integral) functional under some (PDE) constrains. We consider optimal design problems in the setting of the Kirchhoff-Love equation describing an elastic, thin, symmetric plate, which is a fourth order elliptic equation, and we restrict ourselves to domains filled with two isotropic elastic materials. Since the classical solution usually does not exist, we use relaxation by the homogenization method in order to get a proper relaxation of the original problem. Unfortunately, the set of all possible homogenized elastic materials is not known (the famous G-closure problem). However, for the compliance functional, one can overcome this by knowledge of the Hashin-Shtrikman bounds. More precisely, the necessary conditions of optimality are easily derived and expressed via lower Hashin-Shtrinkman bound on the complementary energy, which enables a development of the optimality criteria method for finding an approximate solution.

Thus, we explicitly calculate Hashin–Shtrikman bounds on the complementary energy, and using necessary conditions of optimality, we develop a new variant of optimality criteria method for the single state compliance minimization problems.
This is joint work with Krešimir Burazin and Ivana Crnjac.

Automatic mesh generation for the low order dynamical analysis of marine structures

Domagoj Lacmanović.
University of Zagreb, Faculty of Science

This talk we will present advantages of the utilization of modern open-source mesh generation software in the construction of low degree finite element models of marine structures. Classification societies (CS) require finite element analysis in the case of assessing novel design of marine structures. We will particularly focus on the requirements posed on the mesh generation software for the dynamical (vibrational) analysis. The restrictions posed by CS's safety rules can be expressed as line geometric constraints on the mesh generation routines. Such requirements are typically not implemented in standard mesh generation routines from computer graphics. Further restrictions are posed by the desire to obtain reduced order models through the utilization of low degree shell elements. The usage of such elements poses constraints on the local coordinate systems describing the geometry. We will show how to obtain an optimal mesh which allows for efficient generation of low degree reduced order models. We will further show how to implement the CS's requirements regarding the mesh quality in the open source software gmsh by the use of the geometric preconditioning of the model and will present computational examples from naval architecture praxis which are analyzed with an open source finite element library OOFEM.

Greedy Algorithm for Parameter Dependent Operator Lyapunov Equations. Application to Control Problems

Martin Lazar
Department of Electrical Engineering and Computing, University of Dubrovnik

We provide an efficient method for solving a family of parameter dependent, algebraic Lyapunov equations in an infinite dimensional setting. Our analysis is based on previous work on reduced modeling and (weak) greedy algorithms for parameter dependent PDEs and abstract equations in Banach spaces.
The major contribution is threefold. Firstly, the problem is resolved in an infinite dimensional setting, thus enabling applications to PDEs and equations governed by unbounded operators. Secondly, we demonstrate the boundedness and coercive properties of the Lyapunov operator in appropriate functional spaces. Lastly, the method is applied to the control theory, enabling rapid construction of approximate control functions for a wide range of control problems.

Frequency isolation problem for hyperbolic QEP

Suzana Miodragović
Department of mathematics, University of Osijek

The solution of the forced system undergo large oscillations whenever some eigenvalue of the corresponding quadratic eigenvalue problem

$$\left(\lambda^2 M + \lambda C + K\right) x = 0, \quad 0 \neq x \in \mathbb{C}^n,$$

is close to the frequency of the external force. One way to avoid resonance is to modify matrices M, C and K in such a way that the new system has no eigenvalues close to these frequencies. This frequency isolation problem is considered for the hyperbolic QEP.

Robust control and Stackelberg strategy for a fourth–order parabolic equation

Cristhian Montoya
Department of Electrical Engineering and Computing, University of Dubrovnik

In recent works, the notion of searching for a robust control system is developed simultaneously with a strategy on hierarchic control. From a mathematical point of view, the robustness of a system is equivalent to find a saddle point because we are looking for maximizing the perturbation and simultaneously minimizing the control which stabilizes the system. In addition, a hierarchic control strategy appears on the system, namely, a Stackelberg strategy, which establishes a game between two forces (called follower and leader) into the system. The scheme shows a robust control problem for the *follower control* and its associated disturbance function. Afterwards, we consider a Stackelberg optimization (which is associated to the *leader control*) in order to deduce a controllability result for the Kuramoto–Sivashinsky equation.

H_∞ analysis of cooperative multi-agent systems

Ivica Nakić
Department of Mathematics, Faculty of Science, University of Zagreb

In this talk we study a class of cooperative multi-agent systems described as a network of agents on a graph with the 2nd order dynamics and with decentralized output-feedback policy designed to achieve network synchronization. We are interested in the following question: if one is to disturb (or bolster) one or more agents in order to undermine (or enhance) efforts of other agents or of the entire team, which agent(s) to choose? We will show how this problem can be tackled using tools from control theory.
The talk is based on a joint work with I. Palunko, D. Tolić and Z. Tomljanović.

Learning near-optimal broadcasting intervals in decentralized multi-agent systems using online least-square policy iteration

Ivana Palunko
Department of Electrical and Computer Engineering, University of Dubrovnik

Heterogeneous robot cooperation, robot manipulation of various objects, networked control systems in smart cities, path planning for heterogeneous robots in dynamic environments are examples of systems where adaptive optimal control can be successfully employed. In this talk, problems and results of these algorithms will be presented which enabled these systems to adapt to changing environments while maintaining the sub-optimal performance. Current research activities related to these topics will be presented.

Stabilizing Transmission Intervals and Delays in Nonlinear Networked Control Systems through Hybrid-System-with-Memory Modeling and Lyapunov-Krasovskii Arguments

Domagoj Tolic
Rochester Institute of Technology (RIT), Croatia

This talk presents a hybrid-system-with-memory formalism to attain transmission intervals and delays that provably stabilize Networked Control Systems (NCSs). Nonlinear time-varying plants and controllers with variable discrete and distributed input, output and state delays along with nonconstant discrete and distributed network delays are considered. We bring together nominal system L2-stability, Uniformly Globally Exponentially Stable (UGES) scheduling protocols and linear upper bounds of network-induced output error dynamics to infer Uniform Global pre-Asymptotic Stability (UGpAS) of the closed-loop system via Lyapunov-Krasovskii arguments. The presented methodology allows for more general delays (e.g., multiple input/output/state discrete and distributed delays) and output error dynamics (e.g., multiple discrete and distributed delays) as well as less conservative estimates of Maximally Allowable Transfer Intervals (MATIs). Our results are applicable to control problems with output feedback and the so-called large delays, that is, delays larger than the transmission intervals. In addition, model-based estimators between two consecutive updates, rather than merely the Zero-Order Hold (ZOH) strategy, are allowed for in order to prolong MATIs. Lastly, a nonlinear numerical example involving a single-link robot arm and observer-predictor-based control law is provided to illustrate our theoretical findings.

Optimal damping of vibrational systems using finite time energy criterion

Zoran Tomljanović
Department of Mathematics, J.J. Strossmayer University of Osijek, Osijek

We consider vibration analysis and vibration reduction for mechanical systems. In vibration reduction, the principal goal is to determine an optimal external damping matrix which will ensure optimal evanescence of the system's solution. One can consider different optimality measures for that purpose which depend on particular applications. In this work we introduce a criterion that includes finite time energy criterion. For damping optimization we need to calculate the objective function repeatedly. We propose an approach that is based on structured new formulas where parametric dependence can be used efficiently. Therefore, we are able to calculate finite time energy criterion using the appropriate quadratures rules. We illustrate our approach on numerical examples that consider damped vibrating systems. Joint work with Ivica Nakić and Marinela Pilj Vidaković.

Damping Optimization in Mechanical Systems - New Perspectives

Ninoslav Truhar
Department of Mathematics Josip Juraj Strossmayer, University of Osijek

We consider the damping optimization problem for systems defined by the vector differential equation $M\ddot{x} + C\dot{x} + Kx = 0$, where $M, C, K \in \mathbb{R}^{n\times n}$ are mass, damping and stiffness matrices, respectively.

The optimal damping is obtained as $C_{opt} = \arg_{C\geq 0} \min \operatorname{trace}(X(C))$, where $X(C)$ is a solution of the Lyapunov equation $AX(C) + X(C)A^T = -Z$, A is obtained from M, C, K and Z is an appropriate projector.

We consider two cases: In the first, the mass matrix is singular. For this case, when $\dim(\mathcal{N}(M)) \geq 1$, we introduce a novel linearization, i.e., a novel construction of the matrix A and the novel optimization process. For $\dim(\mathcal{N}(M)) = 1$ we present a novel formula for the solution X of the Lyapunov equation $AX(C) + X(C)A^T = -Z$, with $(C) = 1$ and no internal damping.

In the second case, the mass matrix is positive definite. For this case we present a novel approach for simultaneous optimization of positions and damping viscosities. The position optimization is based on a heuristic for defining a feasible set of possible optimal positions that correspond with local minimizers for the one-dimensional damping acting on only one danger (or dominant) frequency. For this case, we also present a quality analysis for the trace function $f(v) = \operatorname{trace}(X(v))$, which allows us to approximate the trace function as a rational function.
All results are illustrated with a set of numerical examples.

Fast optimization of viscosities for frequency-weighted damping of second-order systems

Matea Ugrica
Department of Mathematics, University of Osijek

We consider frequency-weighted damping optimization for vibrating systems described by a second-order differential equation. The goal is to determine viscosity values such that eigenvalues are kept away from certain undesirable areas on the imaginary axis. To this end, we present two complementary techniques. First, we propose new frameworks using nonsmooth constrained optimization problems, whose solutions both damp undesirable frequency bands and maintain stability of the system. These frameworks also allow us to weight which frequency bands are the most important to damp. Second, we also propose a fast new eigensolver for the structured quadratic eigenvalue problems that appear in such vibrating systems. In order to be efficient, our new eigensolver exploits special properties of diagonal-plus-rank-one complex symmetric matrices, which we leverage by showing how each quadratic eigenvalue problem can be transformed into a short sequence of such linear eigenvalue problems. The result is an eigensolver that is substantially faster than existing techniques. By combining this new solver with our new optimization frameworks, we obtain our overall algorithm for fast computation of optimal viscosities. The efficiency and performance of our new methods are verified and illustrated on several numerical examples.

Application of homogenization to an optimal design problem

Irena Vašiček
Department of Electrical Engineering and Computing, University of Dubrovnik

We will analyse the problem of optimal design for a parabolic equation. The goal of this talk is to find an optimal arrangement of two materials which minimizes given objective function. We allow for a time-dependent composite of materials, with the amount of materials fixed in space and/or time. Since the problem of optimal design is ill-posed in the sense that it does not admit a minimizer, we shall relax the problem using the small amplitude approximation and parabolic H–measures.