Friedrich-Alexander-Universität
DYNAMICS, CONTROL, MACHINE LEARNING AND NUMERICS

Friedrich-Alexander-Universität
Research Center for
Mathematics of Data | MoD

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Alexander-von-Humboldt Professorship
Department of Mathematics
FAU Erlangen-Nürnberg

Unterstützt von / Supported by

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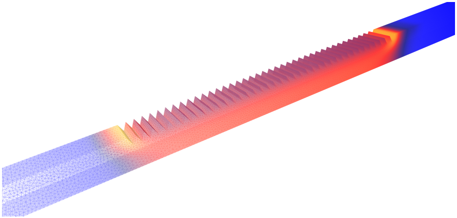
Mission statement

- **Dynamical work environment** at the chair
- Cutting-edge research in the **analysis of partial differential equations**, their **control** and **numerics**
- Development of software for numerical simulation and control



(Blend of mesh and state for 3D simulations)

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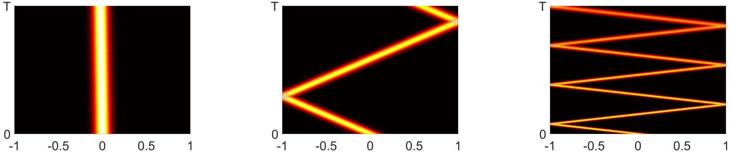

(Rays of geometric optics)

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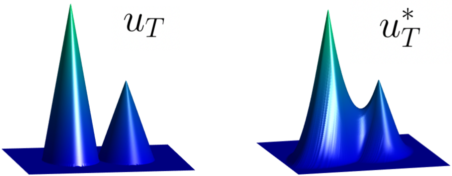
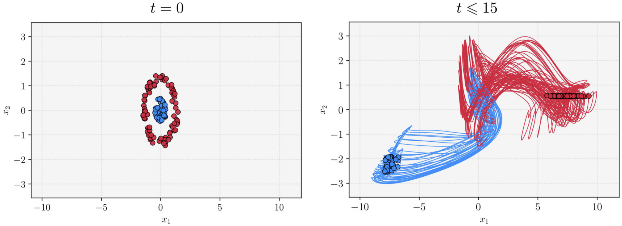


(Semiconcave envelope)

Mission statement

- Establish connections to the emerging and very dynamic field of **machine learning and data science**
- Use control principles to **understand and design** efficient learning algorithms
- **Consolidation of knowledge** at FAU in MoD



(Designing a segmentation learning task by control methods)

Chair for Dynamics, Control and Numerics

- **Alexander-von-Humboldt Professorship**
- Department of Data Science (Bavarian HighTech Agenda)
- Currently **25 team members** from **16 different countries**
  - 3 Professors
  - 8 PostDocs
  - 4 PhD students
  - 5 guest researchers
  - 5 administrative staff
  - 11 previous long-term guests

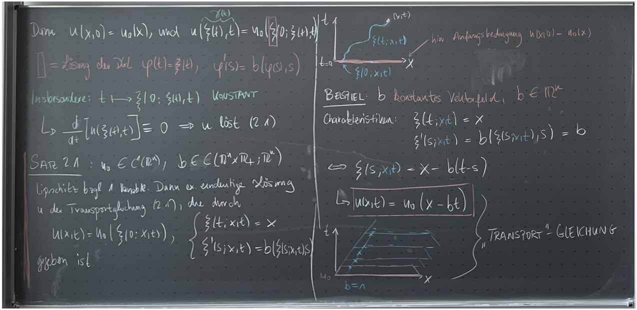
(September 2021, with G. Leugering and J. Sokolowski)

Activities at the chair

- **80 scientific publications** since 2019
- Highly frequented research seminar with international high-profile speakers (more than **40** talks in 2021)
- Biweekly seminar for **junior researchers** in collaboration with the Chair for Applied Mathematics (Modeling and Numerics)
- Internship program for international students and young researchers
- Long-term guest stays for collaborators (Humboldt Foundation funding programs), several guests with stays of 1 month to **1 year**.

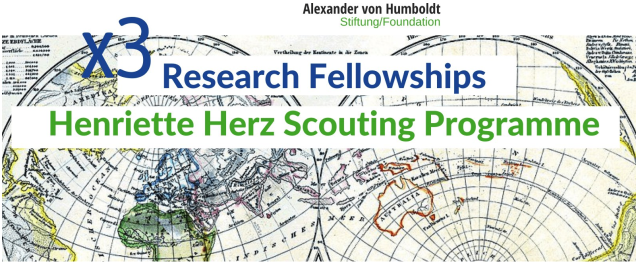
Activities at the chair: Teaching

- Teaching in Mathematics BSc.&MSc., CAM and (new) **Data Science Master** programmes, service for technical faculty
- **New lectures** on connections between control and machine learning
- Practical courses for hands-on experience



(Lecture on transport equations)

Activities at the chair: Henriette-Herz



- DCN chair elected **scout** for the **Henriette Herz Scouting Programme**
- Sponsorship initiative by the **Humboldt Foundation** to attract outstanding young researchers to Germany
- First fellowship holders (Italy/Ukraine) integrated at the chair

Activities at the chair: sherpa.ai

sherpa.ai

Federated Learning: AI's new weapon to ensure privacy.
(MIT Technology Review, 03/2019)

- Tech company supplying a *Privacy-Preserving Artificial Intelligence Platform* based in Bilbao/Spain and Silicon Valley
- **Scientific consulting** for mathematical and algorithmical issues

Activities at the chair: BaCaTeC

- **Bavaria California Technology Center**
- Collaboration with Prof. Dr. Miroslav Krstic (UC San Diego):

  Endowing Artificial Intelligence with Control-Theoretic Guarantees:
  Data-Based Optimization in Real Time for Dynamic Systems

Activities at the chair: TRR154

The turnaround in energy policy concerning social, political and scientific aspects is currently in the main focus of public opinion.
(trr154.fau.de)

DFG CRC TRR154: Mathematical modelling, simulation and optimization using the example of gas networks

Activities at the chair: TRR154

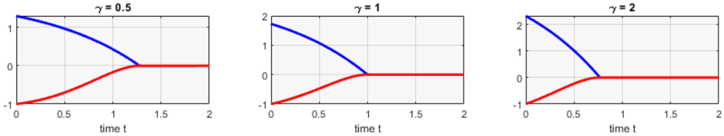
TRR 154

3 projects (current phase), 2 PhD students, 1 PostDoc funded

- Nodal control and the turnpike phenomenon
  (with University Duisburg-Essen)
- Observer-based data assimilation for time dependent flows on gas networks
  (with TU Darmstadt)
- Random batch methods for optimal control of network dynamics
  (with HU Berlin)

Research: TRR154 Subproject C03

Nodal control and the turnpike phenomenon

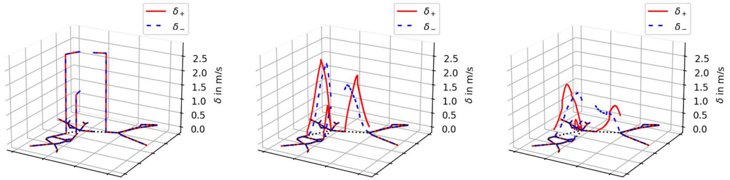


(The Finite Time Turnpike Phenomenon)

- Derivation of different types of turnpike results for **hyperbolic systems on graphs**
- Combination of methods from PDE constrained optimization, mixed integer programming and uncertainty
- Optimal boundary control problems with hyperbolic systems and **probabilistic constraints**

Research: TRR154 Subproject C05

Observer-based data assimilation for time-dependent flows on gas networks

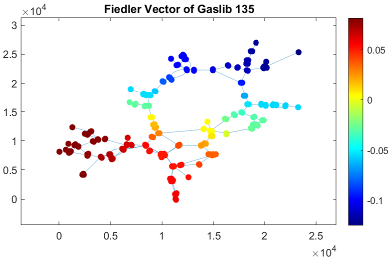


(Observer-based solution for discontinuous initial data and friction)

- **Data assimilation** methods for models of compressible flows in gas networks
- Include measurement data into simulations **during runtime**
- **Augment** original model with control terms that steer the solution towards measured data

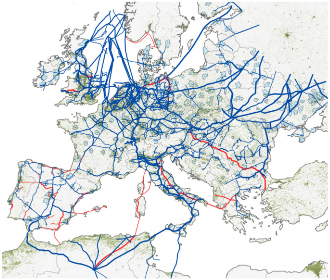
Research: TRR154 Subproject C07

Random batch methods for optimal control of network dynamics



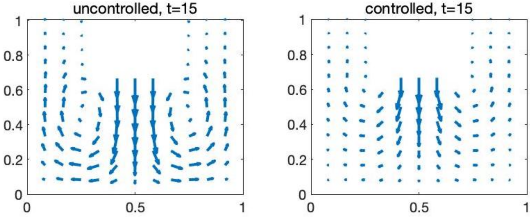
- Developing a **stochastic descent procedure** based on **domain decomposition methods** for the optimal control of network dynamics
- **Spectral graph theory** to find suitable graph decompositions

Research: Optimal design and placement of sensors



- Developing numerical tools for **optimal placement of sensors** on a gas network.
- The optimal placement of sensors will allow to efficiently collect data from the gas network and **prevent possible breakdowns**.

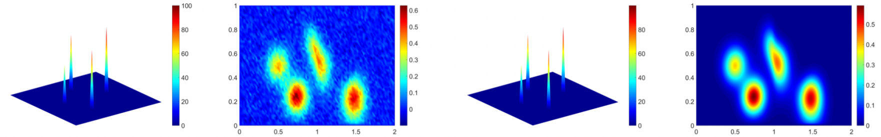
Research: Algorithmic design for optimal control of PDEs



(Vorticity reduction by boundary control of Boussinesq equations)

- Inexact **Uzawa framework** for elliptic optimal control problems
- Inexact **ADMM** for control constrained OC problems
- Numerical methods for bilinear OC of advection-diffusion systems.
- Operator splitting methods for OC of thermally convective flows.

Research: Algorithmic design for inverse problems

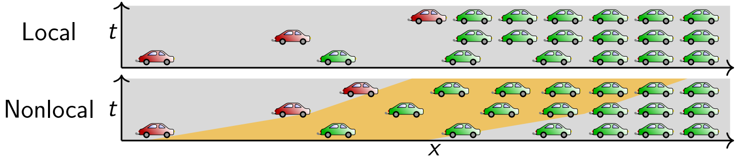


(a) Reference initial state (b) Noisy observation u_T (c) Recovered initial state (d) Recovered final state

(Sparse initial source identification)

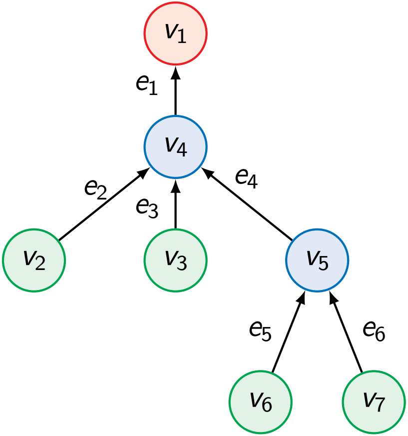
- **Efficient** numerical algorithms for identifying **sparse initial sources** of advection-diffusion systems

Research: Nonlocal traffic models



- Traffic flow models with **nonlocal dynamics**: the velocity depends on a **weighted average of the density ahead**.
- Study existence, uniqueness, long-time behavior, boundary controllability.
- Convergence from **nonlocal to local** behavior when the look-ahead parameter vanishes.

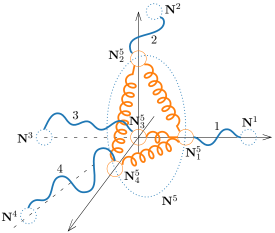
Research: Control of advection-diffusion equations on networks

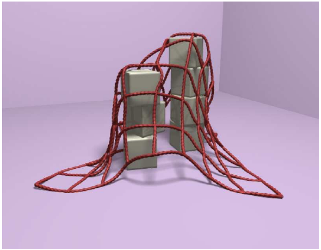


- Contaminant flowing through a network of one-dimensional cracks modeled by advection-diffusion equations on a **tree-shaped graph**.
- **Boundary control** to drive dynamics to a **desired target state**.
- Vanishing diffusivity coefficient.

Research: Analysis and Control of Nonlinear Hyperbolic Systems with Degeneration on Networks

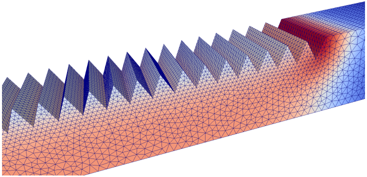
DFG Individual Research Grant



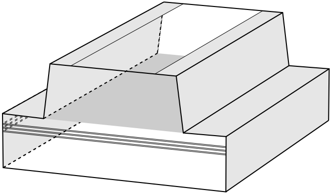


- Control problems for **elastic bodies** arising in particular in structural mechanics
- Develop **sustainable** control strategies with optimal performance respecting the **life-cycle** of the mechanical structures

Research: Analysis & OC of nonlinear evolution equations



(Detail from numerical simulation for Joule heating control)



(Schematic semiconductor device)

- **Quasilinear** parabolic evolution equations with nonsmooth data
- **Boundary control** for **critical** wave equations
- Bilinear control and **renormalized solutions** for Fokker-Planck equations with bounded variation drift

Research: Shape Optimization & Blaschke-Santaló diagrams

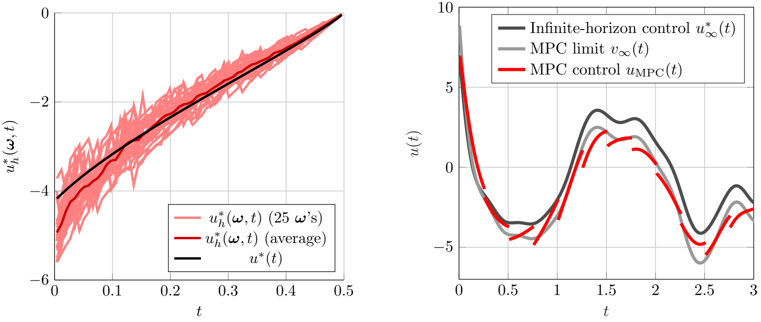
We define the **Cheeger constant** of a bounded subset of $\Omega \subseteq \mathbb{R}^2$ as

$$h(\Omega) := \inf \left\{ \frac{P(E)}{V(E)} \} : \; E \text{ measurable and } E \subseteq \Omega \right\},$$

where $P(E)$ and $V(E)$ are perimeter and the volume of E.

- Derive **sharp estimates** of the Cheeger constant for $\Omega \subset \mathbb{R}^2$ convex via some **purely geometrical functionals**, such as inradius, width, diameter, circumradius, perimeter and area.
- Study of some Blaschke-Santaló diagrams. The aim is to find a **complete system of inequalities**, relating three given shape functionals.

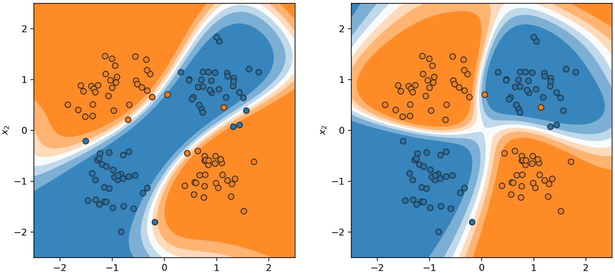
Research: RBM & MPC



Exploring the interface between **control theory**, **numerical analysis**, and **machine learning**.

- Analysis of **Random Batch Methods** (RBMs) in optimal control and their applications in supervised learning.
- Stability & convergence of **Model Predictive Control** (MPC).

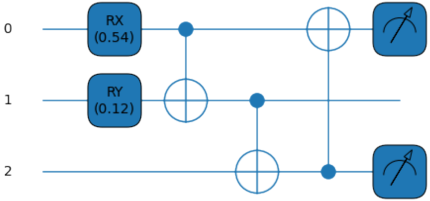
Research: Neural Network Robustness



Classification of Orange and Blue data points.
(Left) Standard training. (Right) Robust training.

- Neural networks are powerful but often vulnerable to manipulations, called **adversarial attacks**
- Design **robust** networks **aided by control theory**.

Research: Quantum computing for Machine Learning



(A quantum circuit)

- Establish connections between the emerging fields of **Machine Learning** and **Quantum Computing** and associated applications.
- Perspective of possible massive **speed up** of numerical algorithms.

Research Center for Mathematics of Data

- Launched in 2020 (Bavarian HighTech Agenda)
- Currently **19 qualified members** from several faculties
  - 17 Professors (including **two Humboldt professorships** and one **German economic expert**)
  - 2 Junior Research Group Leaders
  - 42% women
- **Shared expertise** in these fields (and more):
  - Applied Mathematics
  - Scientific Computing
  - Artificial Intelligence
  - Data Science
- Connections to **all FAU faculties**, to **Max-Planck-Zentrum** für Physik und Medizin, and to **Fraunhofer IIS**
- Create an **interdisciplinary** junior research community

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Thank you!