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SIAM
3600 Market Street, 6th Floor
Philadelphia, PA 19104-2688 U.S.
Telephone: 800-447-7426 (U.S. & Canada) +1-215-382-9800 (Worldwide)
meetings@siam.org

IP1

Control Problems for Multiagent Systems and the Smoothing Traffic via Autonomous Vehicles

Multiagent systems are characterized by the presence of sizable group of agents with some level of autonomy. Examples include crowd dynamics, animal groups, dynamics of socioeconomic systems, and vehicular traffic. Agents are often capable to make decisions and unbalance the energy of the system. Moreover, control actions may be restricted by various limitations, such as controlling a small number of fixed agents. Consequently, control problems become hard both theoretically and practically. We will revise recent advances in modeling and control of multiagent systems illustrating some techniques to deal with the difficulty in control problems. The latter include design sparse controls, controlling by leaders, controls with bounded variation, and mean-field limit techniques. Finally, we will discuss a recent experiment using 100 autonomous vehicles on the I-24 in Nashville area to smooth traffic and increase fuel efficiency. This was the world largest to date experiments with autonomous vehicles on an open highway.

Benedetto Piccoli
Rutgers University
piccoli@camden.rutgers.edu

IP2

Optimal Control: Old and New

This talk is partially a very short overview of a long history of optimal control and partially an intrusion of this theory into Wasserstein metric spaces (of Borel probability measures). Parallels between some well known results on finite dimensional spaces and their analogues in Wasserstein spaces will be discussed. In particular, Hamilton-Jacobi-Bellman Equations and the Maximum principle in Wasserstein spaces will be presented. Wasserstein spaces arise, for instance, in infinite dimensional models approximating large multi-agent systems and recently attracted a big interest because of growing field of applications and also because of a beautiful mathematics behind. Links between differential inclusions and control systems will be emphasized as well.

Hélène Frankowska
CNRS and Sorbonne Université, France
helene.frankowska@imj-prg.fr

IP3

Control and System Theory Methods in Neurostimulation

Electrical stimulation therapies are used to treat the symptoms of a variety of nervous system disorders. Recently, the use of high frequency signals has received increased attention due to its varied effects on tissues and cells. In this talk, we will see how some methods from Control and System Theory can be useful to address relevant questions in this framework when the FitzHugh-Nagumo model of a neuron is considered. Here, the stimulation is through the source term of an ODE and the level of neuron activation is associated with the existence of action potentials which are solutions with a particular profile. A first question concerns the effectiveness of a recent technique called interferential currents, which combines two signals of similar kilohertz frequencies intended to activate deeply positioned cells. The second question is about how to avoid the onset of undesirable action potentials originated when signals that produce conduction block are turned on. We will show theoretical and computational results based on methods such as averaging, Lyapunov analysis, quasi-static steering, and others.

Eduardo Cerpa
Institute for Mathematical and Computational Engineering
Pontificia Universidad Catolica de Chile
eduardo.cerpa@mat.uc.cl

IP4

Optimal Transport and Ambiguity Sets for Swarm Coordination

Self-organization is a pervasive phenomenon in nature that has inspired the development of multi-agent networked systems in a large variety of applications. Optimal transport and related mathematical tools find new application in this context, providing mechanisms for swarm deployment, data-driven learning, and optimal decision making under uncertainty. Motivated by this, in this talk I will present ongoing work that addresses the challenges of design of decentralized algorithms, scalability, and handling of uncertainty for multi-agent systems.

Sonia Martinez
University of California, San Diego
Department of Mechanical and Aerospace Engineering
soniamd@ucsd.edu

SP1

Best Sicon Paper Prize Lecture 1: An Introduction to Graph-Structured Optimal Transport for Estimation and Control

Optimal transport is a classical problem in mathematics that has historically been an important tool in economics and operations research. Recent breakthroughs related to theoretical aspects and numerical solution methods have made it readily available for problems in systems, control, and estimation. The goal of this talk is to give an intuitive introduction to optimal transport and why it is well-suited for problems in estimation and control. The optimal transport problem is to find the most efficient way to morph one distribution into another one. We see that this can be interpreted both as an estimation problem and as an optimal control problem between two distributions. However, many control and estimation settings involve more than two distribution. For instance, a distribution of interest may be observed at different time instances, or by multiple measuring devices. Such problems can be modelled using optimal transport with graphical structures that take into account the relationship between the given distributions. We show that this new framework yields an efficient and flexible tool that allows for addressing a multitude of control related applications. For instance the framework can be used to solve information fusion problems, and optimal control and state estimation problems for ensembles of dynamical systems.

Isabel Haasler
École Polytechnique Fédérale de Lausanne, Switzerland
haasler@kth.se

SP2

Best SICON Paper Prize Lecture 2: CANCELLED - Two-Person Zero-Sum Stochastic

Linear-Quadratic Differential Games

In this talk we study the open-loop saddle point and the open-loop lower and upper values, as well as their relationship for two-person zero-sum stochastic linear-quadratic (LQ, for short) differential games. We shall derive a necessary condition for the finiteness of the lower and upper values and a sufficient condition for the existence of an open-loop saddle point. Under the sufficient condition, it will be proved that a strongly regular solution to the associated Riccati equation uniquely exists, in terms of which we establish a closed-loop representation for the open-loop saddle point. We also present examples to show that the finiteness of the open-loop lower and upper values does not ensure the existence of an open-loop saddle point in general. But for the classical deterministic LQ game, we prove the equivalence of these two issues and obtain an explicit representation for the solution to the Riccati equation.

Jingrui Sun
Southern University of Science and Technology
sunjr@sustech.edu.cn

SP3

2023 W.T. and Idalia Reid Prize Lecture - Duality and Free Boundaries for Optimal Nonlinear Pricing

The principal-agent problem is an important paradigm in economic theory for studying the value of private information; the nonlinear pricing problem faced by a monopolist is one example; others include optimal taxation and auction design. For multidimensional spaces of consumers (i.e. agents) and products, Rochet and Choné (1998) reformulated this problem to a concave maximization over the set of convex functions, by assuming agent preferences combine bilinearity in the product and agent parameters with a (quasi)linear sensitivity to prices. We characterize solutions to this problem by identifying a dual minimization problem. This duality allows us to reduce the solution of the square example of Rochet-Choné to a novel free boundary problem, giving the first analytical description of an overlooked market segment. Based on work with KS Zhang (University of Waterloo) at http://www.math.toronto.edu/mccann/publications

Robert McCann
Department of Mathematics
University of Toronto
mccann@math.toronto.edu

CP1

A Goal-Oriented Multi-Objective Embedded Optimization Problem for Dynamical System Performance Assessment by Deep Learning Techniques

In this talk, we consider a goal-oriented multi-objective embedded optimization problem for dynamical system performance assessment. In particular, our focus is when the objective function for such an optimization problem is a composite of different performance indices corresponding to different operating conditions in the system, and is posed as a goal-oriented multi-objective optimization problem, where the later is represented by neural networks and an attempt is made to solve using deep learning techniques. Here, we also incorporate an adjoint sensitivity analysis in our approach which is an essential aspect in training the embedded neural networks. Finally, a numerical example is presented to illustrate the applicability of the proposed approach and further make comparison with traditional multi-objective optimization techniques such as weighted sum method.

Getachew K. Befekadu
Department of Industrial System Engineering
University of Florida - REEF
getachew.befekadu@morgan.edu

CP1

Modeling and Control of High-Throughput Screening Systems for Drug Discovery and Virus Detection

High-throughput screening (HTS) systems are widely used in biomedical research for analysis of new chemicals, discovery of new drugs, and detection of new viruses. An HTS system is a robotic cell, in which thousands of samples are automatically screened and analyzed in real time. The typical HTS cell involves a fixed set of resources performing liquid handling, storage, reading, plate handling and incubation operations. The samples enter the robotic cell on microplates periodically. The problem under consideration is to find in real time the cyclic schedule of robot moves that minimizes the cycle time which, in turn, maximizes the cell productivity. We are interested to study and model the real-time scheduling and control of the high-throughput screening process under possible changes in input data and in the environment; for this aim, we develop, implement and compare three different algorithmic approaches: Mixed-Integer Programming (MIP), Petri Nets (PN), and PERT/CPM Network Modeling. Computational experiments with the mentioned methods for controlling the real-life HTS systems demonstrated that they can produce the same optimal solution of the problem but with a different complexity. Another, somewhat unexpected, result is that the new version of the PERT/CPM method can generate and control optimal solutions essentially faster than the MIP and PN methods, namely the new advanced PERT/CPM version solves the problem to optimality in strongly polynomial time.

Eugene Levner
Holon Institute of Technology, School of Computer Science,
Holon, Israel
levner@hit.ac.il

Vladimir Kats
Institute for Applied Mathematics, BeerSheva, Israel
¡vlkats@013net.net¿

Pengyu Yan
University of Electronic Science & Technology,Chengdu,China
yanpy@uestc.edu.cn

CP1

Control of Discrete-Time LTI Systems Using Stochastic Ensemble Systems

In this paper, we study the control properties of a new class of stochastic ensemble systems that consists of families of random variables. These random variables provide an increasingly good approximation of an unknown discrete, linear-time invariant (DLTI) system, and can be obtained by a standard, data-driven procedure. Our first result relates the reachability properties of the stochastic ensemble system with that of the limiting DLTI system. We then provide a method to combine the control inputs obtained from the stochastic ensemble systems to compute a control input for the DLTI system. Later, we deal with a particular kind of stochastic ensemble systems generated from realizing Bernoulli random variables. For this, we characterize the variance of the computed state and control. We also do the same for a situation where the data is updated sequentially in a streaming fashion. We illustrate the results numerically in various simulation examples.

Nirabhra Mandal
University of California San Diego
nmandal@ucsd.edu

CP1

Global Boundary Null-Controllability of One-Dimensional Semilinear Heat Equations

This talk addresses the boundary null-controllability of the semi-linear heat equation $\partial_t y - \partial_{xx} y + f(y) = 0$, $(x,t) \in (0,1)\times(0,T)$. Assuming that the nonlinear function f is C^1 over $\mathbb{R}$ and satisfies $\limsup_{|r|\to+\infty} |f(r)|/(|r| \ln^{3/2}|r|) \leq \beta$ for some $\beta > 0$ small enough and that the initial datum belongs to $L^\infty(0,1)$, we prove the global null-controllability using the Schauder fixed point theorem and a linearization for which the term $f(y)$ is seen as a right side of the equation. Then, assuming that f satisfies $\limsup_{|r|\to\infty} |f'(r)|/\ln^{3/2}|r| \leq \beta$ for some β small enough, we show that the fixed point application is contracting yielding a constructive method to approximate boundary controls for the semilinear equation. The crucial technical point is a regularity property of a state-control pair for a linear heat equation with L^2 right hand side obtained by using a global Carleman estimate with boundary observation. Numerical experiments illustrate the results. The arguments developed can notably be extended to the multi-dimensional case.

Arnaud Munch
Université Blaise-Pascal
arnaud.munch@math.univ-bpclermont.fr

CP2

Learning-Based Control of Continuous-Time Systems Using Output Feedback

This paper studies the adaptive optimal control for continuous-time linear systems with output feedback. It aims to fill in the gap in the literature of reinforcement learning and adaptive dynamic programming that has been exclusively devoted to either discrete-time systems or continuous-time systems with full-state information. A key strategy is to utilize the historical continuous-time input-output trajectory to reconstruct the current state. Unlike the convectional state reconstruction methods, the proposed method does not discretize the system dynamics or resort to the state observer. By exploiting the policy iteration (PI) method, sub-optimal output-feedback controllers can be directly obtained from collected input-output trajectory data in the absence of the accurate dynamic model. The effectiveness of the proposed learning-based PI algorithm is demonstrated by means of a practical example of F-16 aircraft control.

Leilei Cui
New York University
l.cui@nyu.edu

Zhong-Ping Jiang
Dept of Electrical and Computer Eng
Polytechnic Institute of NYU
zjiang@poly.edu

CP2

A Learning-Based State Estimation Approach for Model Predictive Control of Integrated Process Networks in the Presence of Cyberattacks

Sustainable development concerns are driving chemical process manufacturing toward highly integrated network designs. Process integration reduces raw material consumption, energy use, and pollution, improving productivity over time. However, integration advantages come with significant automation and control challenges, mainly regarding operational safety and security. We develop an autonomous optimization-based control framework to stabilize complex chemical process networks in the presence of malicious cyberattacks on measurement sensors. The control design integrates moving horizon estimation (MHE) and model predictive control (MPC) to estimate the unmeasured state variables of the system and regulate the controlled outputs at predetermined values with minimum control efforts subject to the path and terminal constraints. A two-tier data-driven cyberattack detection and state reconstruction approach is advanced based on offline process network simulation data to inform the integrated control system about potential corrupted data and reconstruct the falsified measured outputs. The required data is generated by simulating process dynamics over a wide range of manipulated inputs subject to various potential cyberattacks. The restored measures are critical to estimating the unmeasured variables by the MHE, which are then incorporated into the MPC design.

Brayden Sundberg, Davood Pourkargar
Tim Taylor Department of Chemical Engineering
Kansas State University
btsundberg@ksu.edu, dbpourkargar@ksu.edu

CP2

Multi-Agent Reinforcement Learning with Prospect Theory

Recent advances in cyber and cyber-physical systems have informed the development of scalable and efficient algorithms for these systems to learn behaviors when operating in uncertain and unknown environments. When such systems share their operating environments with human users, such as in autonomous driving, it is important to be able to learn behaviors for each entity in the environment that will (i) recognize presence of other entities, and (ii) be aligned with preferences of one or more human users in the environment. While multi-agent reinforcement learning (MARL) provides a modeling, design, and analysis paradigm for (i), there remains a gap in the development of strategies to solve (ii). In this paper, we aim to bridge this gap through the de- sign, analysis, and evaluation of MARL algorithms that recognize preferences of human users using cumulative prospect theory (CPT). To this end, we develop MA-CPT-Q, a multi-agent CPT-based Q-learning algorithm, and establish its convergence. We adapt this algorithm to a setting where any agent can call upon more experienced agents to aid its own learning process, and propose MA-CPT-Q-WS, a multi-agent CPT-based Q-learning algorithm with weight sharing. Our experiments show that agent behaviors after learning policies when following MA-CPT-Q and MA-CPT-Q-WS are better aligned with that of human users who might be placed in the same environment.

Bhaskar Ramasubramanian
Electrical and Computer Engineering
University of Maryland, College Park
ramasub@wwu.edu

Dominic Danis, Parker Parmacek, David Dunajsky
Western Washington University
danisd@wwu.edu, pamacp@wwu.edu, dunajsd@wwu.edu

CP2

Compensation of Disturbance Induced Estimation Bias in Adaptive Dynamic Programming Based Optimal Control

We present a bias compensating adaptive dynamic programming (ADP) learning scheme to address the estimation bias issue encountered in ADP based learning control methods. We consider the classic case of model-free linear quadratic regulator (LQR) augmented with integral control to show that the integral action alone may not be sufficient to prevent estimation bias induced by unmeasurable disturbances in the associated learning equation. It is shown that the presence of unmeasurable disturbances can lead to bias in the estimates of the optimal control parameters, and in extreme cases, the divergence of the algorithm and instability of the system. To address this difficulty, we present a bias compensating ADP learning equation that learns a lumped bias term as a result of disturbances (and possibly other sources) in conjunction with the optimal control parameters. An extension of the standard ADP LQR policy iteration algorithm is presented based on this compensated learning equation. We demonstrate by numerical examples that compared to the uncompensated algorithm, the proposed scheme learns the optimal control parameters without incurring bias.

Syed Ali Asad Rizvi
Tennessee Technological University
Electrical and Computer Engineering
srizvi@tntech.edu

Zongli Lin
University of Virginia
zl5y@virginia.edu

CP2

A Comparative Analysis of Reinforcement Learning and Adaptive Control Techniques for Linear Uncertain Systems

In this paper, we consider uncertain linear systems with input quantizers over communication channels subject to packet loss, and we assume dynamic switching from an unstable state matrix to a more unstable one during the operation. We then investigate the effectiveness of two learning-based control strategies for stabilizing this class of dynamical systems: the Adaptive Quantized Control (AQC) and the Deep Reinforcement Learning (DRL). The adaptive setup assumes acknowledgment messages on packet losses are received by the adaptive controller, while the state matrix is unknown and the input matrix is known. On the other hand, the DRL operates without acknowledgment messages and relies on the knowledge of both the state and input matrices. Results show that DRL outperforms adaptive techniques in damping amplitudes and improving convergence speed. However, when faced with both packet loss and model uncertainty, the mathematical guarantees provided by AQC can better handle stability and uncertainty across a wider range of model parameters

Moh Kamalul Wafi
Northeastern University
wafi.m@northeastern.edu

CP2

Optimal Liquidation of a Basket of Stocks Using Reinforcement Learning

This paper is concerned with the problem of finding optimal buying and or selling strategies to fill large execution orders. Usually, if the execution of large positions is not done efficiently this will result in bad filling prices and break the market equilibrium. Using various techniques from the stochastic control theory, we treat this problem as a discrete-time stochastic control problem with resource constraints. The value function and optimal strategies are obtained in closed form. Numerical examples are reported to illustrate the validity and simplicity of our approach.

Moustapha Pemy
Towson University
Department of Mathematics
mpemy@towson.edu

Na Zhang
Towson
nzhang@towson.edu

CP3

Estimation of Unknown Payoffs Parameters in Large Network Games

We consider a game theoretical setting where a large number of agents interact strategically according to a network and examine a procedure for estimating unknown payoff parameters from observations of equilibrium actions. Importantly, we assume that the planner performing such estimation task does not have access to full network information but instead relies on statistical information about agents interactions, which we represent with a graphon - a flexible nonparametric random graph model. We prove smoothness and local convexity of the optimization problem involved in computing the proposed estimator. Additionally, under a notion of graphon parameter identifiability, we show that the optimal estimator is globally unique, and we obtain global convexity with additional assumptions on the set of parameter values. We present several examples of identifiable homogeneous and heterogeneous parameters in different classes of network games with numerical simulations to validate the proposed estimator.

Feras Al Taha, Francesca Parise
Cornell University
foa6@cornell.edu, fp264@cornell.edu

CP3

Nash-Regularized Control Policy Learning of Linear-Quadratic Zero-Sum Differential Games from Demonstrations

In this paper, we aim to discover the optimal stationary control policies, i.e., Nash equilibrium (NE), of two players in a linear-quadratic (LQ) zero-sum differential game from expert demonstrations. The most straightforward mechanism to learn such players' policies is to use linear pol-

icy fitting, which directly minimizes the loss between the demonstrations and the fitted values. However, this direct policy learning paradigm is not robust to the number of demonstrations and unable to consistently produce a stabilizing control policy, let alone an NE strategy. Therefore, we propose a new learning scheme, called Nash-regularized control policy learning, which restricts the policy obtained in the learning process, preserving the properties of an NE solution. The constraints in the formulated optimization program are bi-linear. Thus, we develop a computational algorithm based on Alternating Direction Method of Multipliers (ADMM) to obtain an approximately optimal solution. The case studies show that the developed Nash-regularized learning can yield more efficient and stable control policies than the direct policy learning method, even with few demonstrations.

Courtney M. King, Juntao Chen
Fordham University
cking74@fordham.edu, jjchen504@fordham.edu

CP3

Graphon Games with Multiple Nash Equilibria: Analysis and Computation

A graphon game can be seen either as a limit of a sequence of network games when the number of players tends to infinity, or as a stochastic model for sampling network games. We show that, under mild conditions which allow for multiple best-responses, every graphon game has a Nash equilibrium. We then show that every convergent sequence of Nash equilibria of sampled network games converges to a Nash equilibrium of the graphon game. Through an example, we show that the converse is not true, i.e., there exist Nash equilibria of graphon games which are not limits of any subsequence of Nash equilibria of sampled network games. Nevertheless, we show that every Nash equilibrium of a graphon game is a limit of a subsequence of ϵ-Nash equilibria of sampled network games, for arbitrarily small $\epsilon > 0$. Thus, all Nash equilibria of graphon games are useful in predicting and prescribing strategies to players in the associated large network games. Finally, we provide methods for computing the Nash equilibria of two broad classes of graphon games modeling commonly observed interaction structures: graphon games with (i) a low-rank graphon and a polynomial best-response function, and (ii) a stochastic block model graphon and finite strategy sets.

Kiran Rokade, Francesca Parise
Cornell University
rokade.kiran94@gmail.com, fp264@cornell.edu

CP3

Robust Control of Linear System with Bounded Control and Disturbance: Revisited

The problem of steering a linear system to a prescribed hyperplane by using a bounded feedback control, robustly with respect to an unknown bounded disturbance, is considered. It is formalized as a finite-horizon zero-sum differential game with linear dynamics and bounded controls. The cost function is the distance between the terminal state and the target hyperplane. The original game is scalarized, and the feedback solution is obtained based on the scalar game space decomposition into the regular and the singular regions. In the regular region, the optimal strategies are of a bang-bang type, and the game value depends on the initial conditions. In the singular region, consisting of a finite number of disjoint subregions, the optimal strategies are arbitrary subject to the constraints, and the game value in each subregion is constant. Singular subregions with zero game value are the capture zones: if the game starts there, the game optimal feedback strategy solves the original robust control problem. In order to guarantee the unique solution, the admissible strategies are redefined. The formula for the singular zone game value is significantly simplified. The main contribution is the algorithm of the game space decomposition for which the determining function is introduced. The decomposition structure depends on its sign changes number. The general recursive (by the number of sign changes) decomposition procedure is proposed. A real-life illustrative example is presented.

Vladimir Turetsky
Braude College of Engineering
turetsky1@braude.ac.il

Valery Glizer
The Galilee Research Center for Applied Mathematics
valgl120@gmail.com

CP4

Modeling Feedback Control Response to Hemodynamic Perturbations in a Pulsatile Circulation Model

Circulation models often treat heart rate as a given parameter. Here, we allow the heart rate to be continuously variable, and we model some of the feedback control mechanisms that influence the heart rate. These include the effects of systemic arterial pressure (which acts through a feedback loop involving the nervous system) and right atrial pressure (which acts directly on the cardiac pacemaker). We use our formulation to examine various perturbations to the parameters of the circulation such as the effects of exercise on a normal physiology as well as a single ventricle physiology known as the Fontan circulation. In particular, we study the effect of control on the Fontan circulation by comparison to results obtained with an uncontrolled model in our previous work. We examine the dynamic effects of the introduction of a surgical modification (fenestration) to the Fontan physiology using our feedback control method. The controlled model accounts for the impact of the fenestration on heart rate, an effect that was neglected in our uncontrolled model. Additionally, we present comparisons between the hemodynamics during exercise in the normal circulation, Fontan circulation, and optimally fenestrated Fontan physiology.

Zan Ahmad
NYU Courant Institute of Mathematical Sciences
Johns Hopkins University Applied Mathematics
zahmad6@jhu.edu

Charles Puelz
Baylor College of Medicine
Department of Pediatrics-Cardiology
charles.puelz@bcm.edu

Charles S. Peskin
Courant Institute of Mathematical Sciences
New York University
peskin@cims.nyu.edu

CP4

Non-Pulsatile ODE Model of Circulation Response

to Hyper-Gravity

The ability to predict the human circulatory system's response to changes in acceleration could improve risk profiling in assessing an individual's capacity to endure the strain of high vertical acceleration (Gz). Previously, we created a steady-state model calibrated with anthropometric measurements to individualize +Gz-tolerance prediction. While this model produced useful preliminary G-tolerance estimations, G-induced Loss of Consciousness (G-LOC) depends on the rate of onset of hypergravity. We present a dynamic model of the cardiovascular system along with simulations. This model is designed to use subject-specific parameters and variable G-profile data for improved predictive outcomes. This ordinary differential equation model is comprised of a thoracic compartment and upper and lower body compartments, with heights determined by subject-specific measurements. The model treats the heart as a continuous flow device, with a time-dependent flow that represents cardiac output. Notable features of the model include an idealized controller that maintains pressure in the upper compartment by changing heart rate and venous reserve volume. Additionally, we model partial venous collapse in the systemic veins entering the thoracic compartment. As this model is non-pulsatile, it has the advantage of being computationally inexpensive and produces readily interpretable results for a subjects G-tolerance while acknowledging the time-dependent nature of G-LOC.

Alanna Kennard
Courant Institute of Mathematical Sciences.
alanna.kennard@gmail.com

Zan Ahmad
NYU Courant Institute of Mathematical Sciences
Johns Hopkins University Applied Mathematics
zahmad6@jhu.edu

Rebecca Blue
University of Texas Medical Branch
Division of Aerospace Medicine
rblue.md@gmail.com

Charles S. Peskin
Courant Institute of Mathematical Sciences
New York University
peskin@cims.nyu.edu

Karen Ong
University of Texas Medical Branch
Aerospace Medicine Division
ong.karen.m@gmail.com

CP4

A Penguin Problem and Pontryagin: Optimal Locomotion of Adelie Penguins over Uneven Terrain

Research on Antarcticas Adelie penguins produced details on the forces and friction experienced by the penguins when they walk or toboggan. Understanding organic motion and decision making allows engineers to design robotic systems and can provide biologists insight to microecosystems. In this work, we are interested in using such studies to create a dynamic optimization problem formulation to predict a penguins method of travel over a terrain. Optimizing the trajectory of a penguin in motion to minimize energy expenditure or travel time can be accomplished through the application of Pontryagins Minimum Principle. To construct an appropriate problem formulation, a mathematical model was developed from previous research on Adelie penguins. Considered was a 2-D, x and y, plane of motion. A continuous terrain function was generated by arraying random slopes and curve fitting a sixth-degree polynomial. Each method of travel (walking and tobogganing) needed different mathematical models to properly capture the penguins dynamics. While walking, the penguin can only use the force of its step to move forward and to stop its motion. When tobogganing, the penguin has the added ability to use its flippers to help propel it forward. Real world limits were placed on velocity and acceleration. It was found that penguins use varying forces to minimize energy usage, over the given terrain and time constraint. Future work should compare these results against observed data.

Angelia M. Otoole
Naval Postgraduate School
Carrizosaa@gmail.com

Mark Karpenko
Department of Mechanical and Aerospace Engineering
Naval Postgraduate School
mkarpenk@nps.edu

CP4

Optimal Control for Rare Event Probability Estimation in Stochastic Biochemical Reaction Networks

We explore efficient estimation of statistical quantities, particularly rare event probabilities, for stochastic reaction networks (SRNs) and biochemical systems. Consequently, we propose an importance sampling (IS) approach to improve the Monte Carlo (MC) estimator efficiency based on an approximate tau-leap scheme. The crucial step in the IS framework is choosing an appropriate change of probability measure to achieve substantial variance reduction. This task is typically challenging and often requires insights into the underlying problem. Therefore, we propose an automated approach to obtain a highly efficient path-dependent measure change based on an original connection in the stochastic reaction network context between finding optimal IS parameters within a class of probability measures and a stochastic optimal control formulation. Optimal IS parameters are obtained by solving a variance minimization problem. We derive an associated dynamic programming equation. Analytically, solving this backward equation is challenging; hence we propose an approximate dynamic programming formulation to find near-optimal control parameters. To mitigate the curse of dimensionality, we pursue two alternative approaches:a learning-based method and a dimension reduction approach. Our analysis and numerical experiments verify that both proposed IS approaches substantially reduce the MC estimators variance, resulting in a lower computational complexity, compared with standard MC estimators.

Sophia F. Wiechert, Chiheb Ben Hammouda
RWTH Aachen University
sophia.wiechert@rwth-aachen.de,
benhammouda@uq.rwth-aachen.de

Nadhir Ben Rached
University of Leeds
n.benrached@leeds.ac.uk

Raúl Tempone
KAUST

RWTH Aachen University
raul.tempone@kaust.edu.sa

CP5

Comparison Theorems for Viscosity Solutions of Hamilton-Jacobi Equations with Co-Invariant Derivatives of Fractional Orders

We consider Hamilton-Jacobi (HJ) partial differential equations (PDEs) with co-invariant derivatives of fractional orders which typically include Hamilton-Jacobi-Bellman PDEs of optimal control and Isaacs PDEs of differential games in fractional order systems. Under a viscosity solution notion given by Gomoyunov using co-invariant derivatives of fractional orders, we discuss comparison theorems for HJ PDEs. A key for the proof is to find an appropriate smooth test functional to measure a distance of two trajectories, however few examples of smooth functionals are known. In this presentation, we propose a new smooth test functional and show comparison theorems for HJ PDEs which might be applicable to characterizations of value functionals of optimal control and differential games in fractional order systems.

Hidehiro Kaise
Graduate School of Engineering Science, Osaka University
kaise@kumamoto-u.ac.jp

CP5

Mean Viability Theorems and Second-Order Hamilton-Jacobi Equations

We introduce the notion of mean viability for controlled stochastic differential equations and establish counterparts of Nagumo's classical viability theorems, i.e., necessary and sufficient conditions for mean viability. As an application, we provide a purely probabilistic proof of existence and uniqueness for generalized solutions of (path-dependent) second-order Hamilton-Jacobi-Bellman equations.

Christian Keller
University of Central Florida
christian.keller@ucf.edu

CP5

Kinodynamic Control Systems and Discontinuities in Clearance

We investigate the structure of discontinuities in clearance (or minimum time) functions for nonlinear control systems with general, closed obstacles (or targets). We establish general results regarding interactions between admissible trajectories and clearance discontinuities: e.g. instantaneous increases in clearance when passing through a discontinuity, and propagation of discontinuity along optimal trajectories. Then, investigating sufficient conditions for discontinuities, we explore a common directionality condition for velocities at a point, characterized by strict positivity of the minimal Hamiltonian. Elementary consequences of this common directionality assumption are explored before demonstrating how, in concert with corresponding obstacle configurations, it gives rise to clearance discontinuities both on the surface of the obstacle and propagating out into free space. Minimal assumptions are made on the topological structure of obstacle sets.

Jeremy LeCrone
Vanderbilt University, Nashville
jlecrone@richmond.edu

Niles Armstrong
Milwaukee School of Engineering
armstrongn@msoe.edu

Jory Denny
Independent Researcher
joryldenny@gmail.com

CP5

An Adaptive Multi-Level Max-Plus Method for Deterministic Optimal Control Problems

We introduce a new numerical method to approximate the solution of a finite horizon deterministic optimal control problem. We exploit two Hamilton-Jacobi-Bellman PDE, arising by considering the dynamics in forward and backward time. This allows us to compute a neighborhood of the set of optimal trajectories, in order to reduce the search space. The solutions of both PDE are successively approximated by max-plus linear combinations of appropriate basis functions, using a hierarchy of finer and finer grids. We show that the sequence of approximate value functions obtained in this way does converge to the viscosity solution of the HJB equation in a neighborhood of optimal trajectories. Then, under certain regularity assumptions, we show that the number of arithmetic operations needed to compute an approximate optimal solution of a d-dimensional problem, up to a precision ε, is bounded by $O(C^d|\log\varepsilon|)$, for some constant $C > 1$, whereas ordinary grid-based methods have a complexity in $O(1/\varepsilon^{ad})$ for some constant $a > 0$.

Shanqing Liu
CMAP
Ecole Polytechnique
shanqing.liu@polytechnique.edu

Marianne Akian
INRIA and CMAP, Ecole Polytechnique
marianne.akian@inria.fr

Stéphane Gaubert
INRIA and CMAP, École polytechnique
stephane.gaubert@inria.fr

CP5

A Computationally Efficient Fundamental Solution for Solution of Certain Nonlinear Control Problems

A finite-horizon nonlinear optimal control problem is considered. The associated Hamiltonian may contain, in addition to standard linear-quadratic terms, running-cost and dynamics components that are nonlinear functions of the state variables. Stat-duality is employed to convert the problem into one in which the only nonlinearity is a running-cost component that is a function of newly appearing control variable, say w. The resulting Hamiltonian contains iterated staticization operations where the staticization over the original (linear-quadratic) control variable is outside the staticization over the newly introduced control variables. Iterated staticization results are generalized to allow an inversion of the order of these operations. This leads to a reformulation of the control problem wherein a fundamental solution is obtained over a newly introduced variable, say q (of state-variable dimension), and initial time. That fundamental solution is obtained from a control problem with control w, of possibly very low dimension, indexed affinely by q. The value function of the original problem is obtained at any state-variable value by application of a max-plus algebra dual operation (analogous to a standard-algebra sense Fourier transform) over q.

William M. McEneaney
Dept. of Mechanical and Aerospace Engineering
University of California, San Diego
wmceneaney@ucsd.edu

Peter M. Dower
Department of Electrical and Electronic Engineering
University of Melbourne
pdower@unimelb.edu.au

CP5

Algorithms for Overcoming the Curse of Dimensionality for Certain Time-Dependent Hamilton-Jacobi Equations Arising in Control Theory and Elsewhere

Hamilton–Jacobi partial differential equations (HJ PDEs) play a central role in many scientific fields, e.g., imaging science, game theory and control theory. Many such HJ PDEs are high-dimensional and can only be solved numerically. Unfortunately, standard grid-based methods for numerical PDEs are not scalable because the computational cost of these methods is exponential in space and time. This issue severely limits the usefulness of HJ PDEs in practice. Recently, several methods have been proposed to try and overcome this issue. One approach relies on the Hopf formula, directly or discretized with a temporal grid, and uses optimization to compute the solution without spatial grids. This approach generally works well, including for certain HJ PDEs with non-convex initial data and time- and state-dependent Hamiltonians, but requires discretizing the Hopf formula with a temporal grid before using an optimization method. This introduces numerical errors and can lead to computationally expensive optimization substeps. In this talk, we present a novel approach that does not require discretizing the Hopf formula with a temporal grid. Instead, we propose using optimization directly on the Hopf formula and then using a temporal discretization only on the optimization substeps. We argue this yields fewer numerical errors and improves computational performance. We illustrate this on bang-bang and finite-horizon linear quadratic optimal control problems.

Gabriel Provencher Langlois, Jérôme Darbon
Brown University
gp2442@nyu.edu, jerome_darbon@brown.edu

CP6

Near-Optimal Control of Dynamical Systems with Neural Ordinary Differential Equations

Optimal control problems naturally arise in many scientific applications where one wishes to steer a dynamical system from an initial state $\mathbf{x}_0$ to a desired target state $\mathbf{x}^*$ in finite time T. Recent advances in deep learning and neural networkbased optimization have contributed to the development of numerical methods that can help solve control problems involving high-dimensional dynamical systems. In particular, the framework of neural ordinary differential equations (neural ODEs) provides an efficient means to iteratively approximate continuous-time control functions associated with analytically intractable and computationally demanding control tasks. Although neural ODE controllers have shown great potential in solving complex control problems, the understanding of the effects of hyperparameters such as network structure and optimizers on learning performance is still very limited. Our work aims at addressing some of these knowledge gaps to conduct efficient hyperparameter optimization. To this end, we first analyze how truncated and non-truncated backpropagation through time affect both runtime performance and the ability of neural networks to learn optimal control functions. Using analytical and numerical methods, we then study the role of parameter initializations, optimizers, and neural-network architecture. Finally, we connect our results to the ability of neural ODE controllers to implicitly regularize control energy.

Lucas Boettcher
Frankfurt School of Finance and Management
Frankfurt, Germany
l.boettcher@fs.de

CP6

Security Investment Over Networks with Bounded Rational Agents: Analysis and Distributed Algorithm

This paper considers the security investment problem over a network in which the resource owners aim to allocate their constrained security resources to heterogeneous targets strategically. Investing in each target makes it less vulnerable, and thus lowering its probability of a successful attack. However, humans tend to perceive such probabilities inaccurately yielding bounded rational behaviors; a phenomenon frequently observed in their decision-making when facing uncertainties. We capture this human nature through the lens of cumulative prospect theory and establish a behavioral resource allocation framework to account for the human's misperception in security investment. We analyze how this misperception behavior affects the resource allocation plan by comparing it with the accurate perception counterpart. The network can become highly complex with a large number of participating agents. To this end, we further develop a fully distributed algorithm to compute the behavioral security investment strategy efficiently. Finally, we corroborate our results and illustrate the impacts of human's bounded rationality on the resource allocation scheme using cases studies.

Jason Hughes
United States Military Academy
jason.hughes@westpoint.edu

Juntao Chen
Fordham University
jchen504@fordham.edu

CP6

Decomposed Resolution of Finite-State Aggregative Optimal Control Problems

A class of finite-state and discrete-time optimal control problems is introduced. The problems involve a large number of agents with independent dynamics, which interact through an aggregative term in the cost function. The problems are intractable by dynamic programming. We describe and analyze a decomposition method that only necessitates to solve at each iteration small-scale and independent optimal control problems associated with each single agent. When the number of agents is large, the convergence of the method to a nearly optimal solution is ensured, despite the absence of convexity of the problem. The procedure is based on a method called Stochastic Frank-Wolfe algorithm, designed for general nonconvex aggregative optimization problems. Numerical results are presented, for a toy model of the charging management of a battery fleet.

Kang Liu
CMAP, Ecole Polytechnique, CNRS,
Institut Polytechnique de Paris
kang.liu@polytechnique.edu

Nadia Oudjane
OSIRIS department, EDF Lab, Paris-Saclay
nadia.oudjane@edf.fr

Laurent Pfeiffer
Inria and CMAP, Ecole Polytechnique, IPP
laurent.pfeiffer@inria.fr

CP6

Model Predictive Control for Urban Traffic Signals with Stability Guarantees

Traditional traffic signal control focuses more on the optimization aspects whereas the stability and robustness of the closed-loop system are less studied. This paper aims to establish the stability properties of traffic signal control systems through the analysis of a practical model predictive control (MPC) scheme, which models the traffic network with the conservation of vehicles based on a store-and-forward model and attempts to balance the traffic densities. More precisely, this scheme guarantees the exponential stability of the closed-loop system under state and input constraints when the inflow is feasible and traffic demand can be fully accessed. Practical exponential stability is achieved in case of small uncertain traffic demand by a modification of the previous scheme. Simulation results of a small-scale traffic network validate the theoretical analysis.

Tong Liu
New York University
tl3049@nyu.edu

Qichao Wang
National Renewable Energy Laboratory
qichao.wang@nrel.gov

Hong Wang
Oak Ridge National Laboratory
wangh6@ornl.gov

Zhong-Ping Jiang
New York University
zjiang@nyu.edu

CP6

Traffic Flow Dynamics in Presence of Bottleneck and Adaptive Speed Planning Controller

The presence of bottlenecks such as slow-moving vehicles or exit ramps creates traffic jams. Joining more vehicles in these congested areas causes various complications including the inefficiency of fuel consumption and undesired traffic behavior. In this talk, we will discuss the speed planning controller that is designed to assist Connected Automated Vehicles (CAV) in adaptively controlling their speed to avoid contributing to the existing traffic jam. While such a controller is shown to be very helpful in improving traffic behavior in practice, the performance strongly depends on a careful understanding of the corresponding traffic dynamics. We discuss the traffic behavior as a solution to a strongly coupled PDE-ODE Cauchy problem. In particular, we discuss the solution to

$$\begin{cases} \partial_t \rho + \partial_x [f(\gamma, \rho)] = 0 & , x \in \mathbb{R},\, t \in \mathbb{R}_+ \\ \rho(0, x) = \rho_\circ(x) \\ f(\gamma, \rho) - \dot{y}\rho \leq F(y) \\ \dot{y} = w(y, \rho) \end{cases} .$$

The solution ρ denotes the density, f is the flow and γ captures the variable speed limits. The last dynamic explains the bottleneck trajectory $t \mapsto y(t)$ that is fully coupled with the conservation law through the bottleneck capacity constraint in the third inequality. The properties of the solution and the corresponding numerical methods will be elaborated.

Hossein Nick Zinat Matin
University of California at Berkeley
h-matin@berkeley.edu

Maria Laura Delle Monache
UC Berkeley
Assistant Professor
mldellemonache@berkeley.edu

CP6

Risk-Aware Decision Making for Autonomous Driving with Theory of Mind

As autonomous vehicles become popular, the importance of designing automated driving systems (ADS) to ensure safety cannot be understated. One challenge in designing effective ADS is to characterize decision-making when obstacles (e.g., pedestrians, cars) occlude the field of vision of the ADS. Our objective is to equip ADS-enabled vehicles with human-like decision making. When faced with imprecise knowledge of road conditions, human drivers have been known to base their decisions (e.g., change lanes) on the reactions of other drivers. In psychology research, the ability to reason about behaviors of other humans by ascribing ‘mental states to them is called the Theory of Mind [Bard, et al., The Hanabi Challenge, AI Journal, 2020]. In this paper, we use theory of mind to characterize decision making of ADS-enabled vehicles. Using a POMDP model, the ADS uses behaviors of other entities on the road in a partially observable environment to fill gaps in its own observations (e.g., due to blind spots). Our solution technique estimates the current level of driving risk and categorizes behaviors into discrete states. These states are used to synthesize a policy for the ADS in a manner that minimizes the probability of collisions on the road. We validate our algorithms through experiments on the Nocturne [Vinitsky, et al., Nocturne: A scalable driving benchmark, arXiv, 2022] driving simulator to demonstrate coordination among multiple agents in partially observable environments.

Bhaskar Ramasubramanian
Electrical and Computer Engineering
University of Maryland, College Park
ramasub@wwu.edu

Tyler Roque, Minh Le, Dominic Danis
Western Washington University

roquet@wwu.edu, lem7@wwu.edu, danisd@wwu.edu

CP7

Data-Driven Control of An Inverted Pendulum System

Control systems are essential in maintaining the stability and performance of systems in a broad range of fields. However, controlling systems with processing power constraints, such as embedded systems, is a challenging task. In this work, we propose a control solution based on a neural network. Our low-complexity neural network imitates a model-predictive controller and requires limited computational resources, thus it can be implemented on micro-controllers. Our data-driven control framework is trained in simulation based on the system's dynamics and then validated in a more realistic environment. We show the effectiveness of our proposed neural network controller by successfully stabilizing an inverted pendulum in a real-world system with low computational effort.

Yizhak Abu
Technion
yizhak@campus.technion.ac.il

Tom Hirshberg
Technion, Israel
tomhirshberg@campus.technion.ac.il

Alex Bronstein
Department of Computer Science
Technion - Israel Institute of Technology
bron@cs.technion.ac.il

CP7

Approximate Current State Observability of discrete-Time Nonlinear Systems under Cyber-Attacks

Widespread use of the Internet and other means of communication has increased the risk of cyber-attacks that can affect the warranted operation of a system. To prevent damages from attacks, an assessment of its security plays an important role in providing fast and reliable solutions. This talk focuses on state estimation of nonlinear systems under attacks. We consider a plant represented by a discretetime nonlinear system and an attacker modeled as a finite state machine. We propose a novel notion of observability, called approximate current state observability under attacks, which corresponds to the possibility of identifying the current state of the plant after a given transient despite the malicious action of an attacker that can replace the plant output symbols in the communication network infrastructure. To provide conditions for this property to hold, we resort to the use of formal methods and in particular, of symbolic models. Symbolic models provide an abstract description of purely continuous systems, where a symbolic state corresponds to an aggregate of continuous states in the original system. The approach we propose is particularly useful when dealing with cyber-security of purely continuous processes in that it offers a framework to deal with the heterogeneous models of the plant and the attacker. An academic example showing the applicability of the results presented is offered.

Elena De Santis, Maria Domenica Di Benedetto,
Giordano Pola
University of L'Aquila
elena.desantis@univaq.it, mariadomenica.dibenedetto@univaq.it, giordano.pola@univaq.it

CP7

Controller Design for Unstable Time-Delay Systems: Trade-Offs on Robust Stability, Tracking and Disturbance Rejection

In this presentation we will review the results of our recent work, (Systems Control Letters, vol.172, Feb. 2023, 105453), on robust stability of SISO systems with time delays, and discuss extension to MIMO case. Consider an unstable LTI plant with time delay $P(s) = P_o(s)e^{-hs}$, where P_o is finite dimensional, $h > 0$ is the delay. Let r be the reference input and v be the disturbance for the two-degree of freedom control system whose output y is obtained from

$$Y = P\ U\ , \quad U = C_o\ (R - H\ Y) + V,$$

where C_o and H are to be designed. Let K be designed for P_o considering stability and tracking performance of the non-delayed system. Then define

$$C_o = Q_o(I - He^{-hs}P_oQ_o)^{-1}\ , \quad Q_o := K(I + P_oK)^{-1}.$$

The feedback system is stable if K stabilizes P_o and $(I - He^{-hs})P_o$ is stable. For stability robustness to mismatch in delay and other unmodeled dynamics in the plant, the stable filter H is designed to satisfy

$$\|H\|_\infty \le 1/\|W_mT_o\|_\infty \tag{1}$$

where W_m is a weight capturing the multiplicative plant uncertainty. Thus, the design for H is a Nevanlinna-Pick interpolation problem. In this presentation we will give examples of this design, its extension to MIMO plants, and discuss trade-offs between robust stability, tracking performance and disturbance rejection properties of the feedback system.

Hitay Ozbay
Bilkent University, Turkey
hitay@bilkent.edu.tr

Mustafa Oguz Yegin, Yusuf Baran Ates
Bilkent University
Ankara, Turkey
yegin@ee.bilkent.edu.tr, yusufbaranates@gmail.com

CP7

Design of State Feedback Controller for Fractional-Order Singular Systems with Time Delays

In this study an effective method is introduced to stabilize fractional-order singular time-delay systems, while time-delay can belong to a specified interval from zero to a given amount of delay. A new approach to decompose fractional-order singular time-delay systems (FOSTDSs) and transform them to normal fractional-order time-delay systems (FOTDSs) with a lower order is presented. Also, as this decomposition reduces the order of the system, reducing the computational complexity is one of the important benefits of this method. Then, a stabilization method is provided to stabilize the linear singular fractional delay systems in a range of zero to one given delay. By presenting three examples in this paper, the applicability and effectiveness of this method are shown.

Mohammadali Pakzad
Department of Electrical Engineering

Science and Research Branch, Islamic Azad University
m.pakzad@srbiau.ac.ir

CP7

Observer Based Robust Resilient Control for Nonlinear Semi Markovian Jump Systems: IT2 Fuzzy Approach

This study investigates the input-output finite-time stability (IO-FTS), which includes FTS to the input-output paradigm for a class of semi-Markovian jump systems with uncertainties and disturbances, using the interval type 2 fuzzy approach. In order to tolerate the adverse effects of controller fragility while ensuring robust performance, observer-based resilient robust control is developed to achieve system stability. Additionally, the fuzzy controller is constructed using a non-parallel distributed compensation strategy, intensifying the system's versatility. Furthermore, sufficient conditions for achieving the IO-FTS are derived by considering the appropriate Lyapunov candidate and employing Lyapunov stability theory and stochastic analysis via a linear matrix inequality approach with H_∞ performance. The developed conditions are solved to get the controller and observer gain matrices. Then the potential of the theoretical finding is finally validated by simulations with examples.

Aarthi S
Research Scholar
aarthi15.au@gmail.com

CP8

A Kernel-Based Machine Learning Method for Schrdinger Bridges

We propose a kernel-based machine learning method for numerical solutions of Schrdinger's bridge problems. In this method, the terminal time distribution constraint is described by a kernel-based metric on the space of probability measures.

Yumiharu Nakano
Graduate School of Innovation Management
Tokyo Institute of Technology
nakano.y.ai@m.titech.ac.jp

CP8

Error Bounds for Kernel-Based Approximations of the Koopman Operator

We consider the data-driven approximation of the Koopman operator for stochastic differential equations on reproducing kernel Hilbert spaces (RKHS). Our focus is on the estimation error if the data are collected from long-term ergodic simulations. We derive both an exact expression for the variance of the kernel cross-covariance operator, measured in the Hilbert-Schmidt norm, and probabilistic bounds for the finite-data estimation error. Moreover, we derive a bound on the prediction error of observables in the RKHS using a finite Mercer series expansion. Further, assuming Koopman-invariance of the RKHS, we provide bounds on the full approximation error. Numerical experiments using the Ornstein-Uhlenbeck process illustrate the results.

Friedrich Philipp
Technische Universität Ilmenau
friedrich.philipp@tu-ilmenau.de

CP8

General Markov Decision Process Framework for Directly Learning Optimal Control Policies

We consider a new form of decision making under uncertainty that is based on a general Markov decision process (MDP) framework devised to support opportunities to directly learn the optimal control policy. Our MDP framework extends the classical Bellman operator and optimality criteria by generalizing the definition and scope of a policy for any given state. We establish convergence and optimality results-both in general and within various control paradigms (e.g., piecewise linear control policies)-for our control-based methods through this general MDP framework, including convergence of Q-learning within the context of our MDP framework.

Yingdong Lu
IBM T. J. Watson Research Center
yingdong@us.ibm.com

Mark Squillante
IBM Research
mss@us.ibm.com

Chai Wah Wu
IBM T. J. Watson Research Center
cwwu@us.ibm.com

CP8

Fast Policy Iteration for Multiscale Markov Decision Processes.

Singularly perturbed Markov decision processes (MDPs) provide a framework to model control and dynamic-decision making problems where the underlying dynamics exhibit multiscale structure. The exact model of this problem is ill-conditioned and computationally challenging. Although an aggregated model with asymptotic optimality was proposed, it suffers from the curse of dimensionality, as the number of actions is exponential to the number of actions in the exact model. In this paper, we propose a fast policy iteration algorithm for solving this problem exactly. In particular, the policy evaluation step is accelerated by making use of both the aforementioned aggregated model and multilevel optimization methods. As opposed to the existing methods which also make use of the aggregated model, our method does not suffer from the curse of dimensionality. We provide the convergence analysis and the computational complexity of the proposed algorithm, and demonstrate that the proposed method outperforms the other methods in the numerical experiments.

Qiuhao Wang, Chin Pang Ho
City University of Hong Kong
jerrison.wang@my.cityu.edu.hk, clint.ho@cityu.edu.hk

CP9

Depinning of Domain Walls in a Notched Ferromagnetic Nanostrip with Inertial and Nonlinear Dissipative Effects

In this work, we investigate the static and kinetic depinning field of a domain wall in a notched magnetic nanostrip in the framework of the Landau-Lifshitz-Gilbert equation combined with inertial and nonlinear dissipative effects. We focus our attention on the impact of viscous, dry-friction, and inertial dissipations on the domain wall propagation. More precisely, dry-friction dissipation significantly affects the depinning field, whereas viscous dissipation influences the average domain wall velocity profile. A detailed assessment of the pinning and depinning dynamics and the consequences of nonlinear dissipations and inertial effect is provided by adopting a Walker-type trial solution and employing numerical simulations. Overall, our study provides crucial insights into the intricate dynamics involved in the depinning of domain walls in the context of notched magnetic nanostrips.

Sarabindu Dolui
NATIONAL INSTITUTE OF TECHNOLOGY
ANDHRA PRADESH
doluisarabindu@gmail.com

CP9

Nonlinear Feedback Controllers for Extended Convective Brinkman-Forchheimer Equations

The following extended convective Brinkman-Forchheimer (eCBF) equations perturbed by a subdifferential

$$\frac{\partial \boldsymbol{y}}{\partial t}-\mu\Delta\boldsymbol{y}+(\boldsymbol{y}\cdot\nabla)\boldsymbol{y}+\beta|\boldsymbol{y}|^{r_1-1}\boldsymbol{y}+\alpha|\boldsymbol{y}|^{r_2-1}\boldsymbol{y}+\nabla p+\partial \mathrm{I}_K(\boldsymbol{y}) \ni \boldsymbol{g},\ \nabla\cdot\boldsymbol{y}=0,$$

in a d-dimensional torus is considered, where $d \in \{2,3\}$, $\mu, \beta > 0, \alpha \in \mathbb{R}$ and $r_1 \in [1,\infty)$ with $r_1 > r_2 \geq 1$ and I_K is the indicator function for a given convex set K. We prove the feedback stabilization (by finite and infinite dimensional controllers) of eCBF equations which preserve some invarinace condition for a given convex set by establishing the existence and uniqueness of weak as well as strong solutions for eCBF equations. The well-posedness of the problem is achieved by using the abstract theory for m-accretive operators.

Sagar Gautam
Indian Institute of Technology Roorkee - IIT Roorkee
India
sagar_g@ma.iitr.ac.in

CP9

Approximate Controllability of Semilinear Differential Inclusion with Nonlocal Conditions

We study the approximate controllability of the abstract semilinear differential inclusion with nonlocal inclusion conditions via semigroup theory in reflexive Banach spaces. We assume the compactness of the corresponding evolution family and the approximate controllability of the associated linear control system and define the control with the help of duality mapping. We observe that convexity is essential in determining the controllability property of semilinear differential inclusion. In the case of Hilbert spaces, there is no issue of convexity as the duality map becomes simply the identity map. In contrast to Hilbert spaces, if we consider reflexive Banach spaces, there is an issue of convexity due to the nonlinear nature of duality mapping. The novelty of this paper is that we tackle the convexity issue mentioned above and establish our main result.

Bholanath Kumbhakar
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
bkumbhakar@mt.iitr.ac.in

Dwijendra N. Pandey
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India.
dwij@ma.iitr.ac.in or dwij.iitk@gmail.com

CP9

Interior Approximate Controllability a Fractional Parabolic-Elliptic Coupled System

We analyse the interior approximate controllability of a fractional parabolic-elliptic coupled system with integral memory terms involving the state solution. The system is submitted to the homogeneous Dirichlet type exterior condition. The control is located in the parabolic equation and acts on a non-empty open set $\mathcal{O}$ of the bounded open set Ω. To obtain the main result, we begin by establishing, by the semigroup method and using Galerkin's approximations, the existence and uniqueness of a weak solution of systems approximating the studied one. Then we show well-posedness results for the dual equation. Lastly, a unique continuation property for the dual equation is stated. The latter allows us to prove the approximate controllability results, at any time $T > 0$ and for every control in $\mathcal{D}(\mathcal{O}\times(0,T))$, for the approximated system then for the initial system by making ε tends to 0.

Carole Louis-Rose
Université des Antilles
carole.louis-rose@univ-antilles.fr

CP9

A Geometric Perspective on Differential Flatness in Mechanical Systems with Symmetry

In this talk, we illustrate a geometric perspective on the well-known property of differential flatness in the setting of mechanical systems with symmetry. In view of the principal bundle structure emerging on the configuration manifold from the symmetry in the dynamics, we identify a class of flat outputs comprising the group variables of a local trivialization of the bundle. We call these geometric flat outputs, because they are group-valued, equivariant, and often globally or almost globally defined, as shown in our previous work [”The Role of Symmetry in Constructing Geometric Flat Outputs for Free-Flying Robotic Systems”, ICRA 2023]. We show that many classical examples of flat outputs can be seen to be geometric flat outputs, and we present a sufficient condition for the construction of such an output. Under a mild regularity assumption, the condition amounts to the existence of a local section of the bundle which is orthogonal to a distribution determined by the kinetic energy metric and the distribution of unactuated velocities. The results afford insight into open questions regarding the intuitive geometric form of known flat outputs of many mechanical systems, as well as the absence of global flat outputs for systems on nontrivial bundles (which lack global sections). Such group-valued flat outputs also suggest promising possibilities for formally extending flatness-based planning and control algorithms beyond local regions of the configuration manifold.

Jake Welde
University of Pennsylvania
GRASP Laboratory
jwelde@seas.upenn.edu

Matthew D. Kvalheim
University of Michigan
kvalheim@umich.edu

Vijay Kumar

University of Pennsylvania
GRASP Laboratory
kumar@seas.upenn.edu

CP10

Modal Sensitivity and Ellipsoidal Quality Estimates of Multidimensional Control Systems

Ia problem under consideration is connected with the necessity to ensure stability of ellipsoidal estimates of quality of multidimensional continuous control systems functioning under the conditions of variations or uncertainty of parameters of their structural elements, and consequently, with the development of technology of assessment of their instability caused by the mentioned factors.

Taalaibek Akunov, Roman Omorov, Akylai Akunova
MRAI KR NAS
takunov@mail.ru, romano_ip@list.ru, aakunova@mail.ru

CP10

Goh and Legendre-Clebsh Conditions for Nonsmooth Control Systems

Higher order necessary conditions for a minimizer of an optimal control problem are generally obtained for systems whose dynamics is continuously differentiable in the state variable. Here, by making use of the notion of set-valued Lie bracket, introduced in [?], we obtain Goh and Legendre-Clebsh type conditions for a control affine system with Lipschitz continuous dynamics. In order to manage the simultaneous lack of smoothness of the adjoint equation and of the Lie bracket-like variations, we make use of the notion of Quasi Differential Quotient, introduced in [?]. We also show exhibit some examples where the established higher order condition is capable to rule out the optimality of a control verifying a first order Maximum Principle.

Francesca Angrisani
niversity of L'Aquila
francesca.angrisani@univaq.it

CP10

Solvability of Semilinear Operator Equations with Growing Nonlinearity Using Tikhonov Regularization

In this paper, we prove approximate solvability of the semilinear operator equation $Lu+Nu = v$ using Tikhonov regularization and Browder's fixed point theorem under the following assumptions: (i) The corresponding linear operator equation $Lu = v$ is approximately solvable. (ii) The nonlinear operator $N : U \to V$ is compact. (iii) $\|Nu\| \leq a+b\|u\|$ for some positive constants a and b with $b < \frac{2\sqrt{\lambda}}{1+\frac{1}{2\sqrt{\lambda}}}$ where $\lambda > 0$ is a regularization parameter. Theory is substantiated with an application for computing regularized control for approximately controllable semilinear control system.

Ravinder Katta
IIITDM Kurnool
ravinder@iiitk.ac.in

N. Sukavanam
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India.
n.sukavanam@ma.iitr.ac.in

CP10

Quantization Based Enhanced Equivalent-Input Hybrid-Triggered Control for Memristor Chuas Circuit

In this work, the stabilization and enhanced disturbance rejection technique for repeated scalar nonlinear systems using hybrid-triggered control is discussed. In order to stabilize and reduce the communication burden, hybrid-triggered control is proposed for the considered system. To be more specific, a Bernoulli distributed stochastic variable describes the switching rule of data transmission. Further, an enhanced equivalent-input disturbance technique is implemented to the control in order to suppress the effects of external disturbances, which are unavoidable in the practical systems. As a result, high accuracy estimations of the unexpected external disturbances are established on the basis of the proposed control scheme. On the other hand, quantization is an effective technique to endure the control requirement. Since the system may lead to performance deterioration and sometimes cause instability. Hence, the signals or information should be quantized before they are transmitted to the corresponding components of the control system. In the perspective of linear matrix inequalities, Lyapunov stability theory is used to construct a set of essential conditions to ensure the system is asymptotically stable. To represent the merits of the proposed control technique, numerical results for memristor Chuas circuit was included.

Asha Safana M
Anna University
asharaseen.au.math@gmail.com

CP10

Simulation of Control for Riemann-Liouville Fractional Evolution Systems Using Tikhonov Regularization

In this paper, we simulate the control for a system of Riemann-Liouville fractional differential equations using the technique of Tikhonov regularization. Simulating the control for the considered system (approximately controllable) corresponds to the ill-posed problem formulated with the help of the controllability operator. The method of Tikhonov regularization is applied to obtain stable approximations of the ill-posed equation. Detailed numerical validation of the proposed methodology and the error involved in the regularization procedure is performed for a kind of fractional heat equation. Two-dimensional solution graph at final time and three-dimensional graphs of the truncated control for different choices of parameter involved are drawn.

Lavina Sahijwani
Department of Mathematics
Indian Institute of Technology Roorkee, Roorkee,
Uttarakhand
sahijwani.lavina@gmail.com

N. Sukavanam, Dwijendra N. Pandey
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India.
n.sukavanam@ma.iitr.ac.in, dwij@ma.iitr.ac.in or

dwij.iitk@gmail.com

MS1

Detecting and Exploiting Symmetry to Accelerate Reinforcement Learning

Reinforcement learning can be used to develop a feedback control policy for an autonomous system when the system's dynamics aren't known explicitly but can be explored through simulations or physical experiments. When a symmetry is present, this fact can be exploited to accelerate exploration and learning. It's possible to know in advance that a particular symmetry will be present in a particular problem — for instance, when a mobile robot with unknown internal dynamics moves through an environment with some known uniformity — but it's also possible to detect unknown symmetries during the learning process. The detection of a symmetry while learning can be used to trigger the exploitation of that symmetry, accelerating learning thereafter. We illustrate these ideas using computational models for two systems: a wheeled mobile robot learning to navigate in a particular spatial direction and an array of vibrating cylinders driving a planar viscous streaming flow to advect an inertial solid particle to a target location. The former example is contrived, in that an analytical model is available for model-based control design, but only a computational model exists for the latter system, and our control results for this system are novel.

Scott Kelly
University of North Carolina at Charlotte
North Carolina
gscottkelly@gmail.com

MS1

Pressure Stabilized POD Reduced Order Model for Control of Fluids

In this paper, we propose a new pressure-stabilized proper orthogonal decomposition reduced order model (POD-ROM) for the control of viscous incompressible flows. It is a velocity-pressure ROM that uses pressure modes as well to compute the reduced order pressure needed for instance in the control drag and lift forces on bodies in the flow. We also propose and analyze a decoupled time-stepping scheme that uncouples the computation of velocity and pressure variables. It allows us at each time step to solve linear problems, uncoupled in pressure and velocity, which can greatly improve computational efficiency. Numerical studies are performed to discuss the accuracy and performance of the new pressure-stabilized ROM in the simulation of control of flow past a forward-facing step channel.

S.S. Ravindran
University of Alabama in Huntsville
ravinds@uah.edu

MS1

Data-Driven Coarse Graining of Vortex Shedding for Flow Control

The complex Ginzburg-Landau equation (CGLE) models the dynamics of a wide range of phenomena, including fluid flows and flow control applications. The study of such reduced-order models (ROMs) can benefit the understanding of the original phenomena and vice versa. In this work, we present the discovery and development of a new Landau variable for the CGLE in the case of vortex shedding behind a 2D cylinder. After obtaining flowfield data from a CFD simulation, we coarse-grain and time-delay embed the data. We then use SINDy, a data-driven method, to generate a sparse, interpretable model that explains the dynamics with minimal error. We close by exploring flow control applications and extensions of SINDy for control.

Joseph J. Williams
University of Washington
USA
jjw2678@uw.edu

Steven Brunton
University of Washington
sbrunton@uw.edu

MS2

Energy-Based Approximation of Linear Systems with Polynomial Outputs

Abstract: Observability and controllability energies play a fundamental role in model reduction by balanced truncation. For the case of linear dynamical systems whose output functional is a polynomial of order m we show that the controllability energy functional is a polynomial whose order is exactly $2m$. Furthermore, we demonstrate that the coefficients of this polynomial representation can be computed by solving linear systems that exhibit a tensor structure. The new polynomial forms for the energy functions allow for deriving a balanced truncation procedure for systems with polynomial outputs. Leveraging techniques for low-rank solution approximations of tensor strucutred linear systems we demonstrate the scalablity of the proposed approach.

Linus Balicki
Virginia Tech
Blacksburg, USA
balicki@vt.edu

MS2

Nonlinear Balanced Truncation for Quadratic Bilinear Systems

We present a numerical method to implement nonlinear balancing on quadratic-bilinear (QB) systems. Using Kronecker-product-based polynomial expansions of the nonlinear energy functions used for balancing, we convert the Hamilton-Jacobi-Bellman Partial Differential Equations (HJB PDEs) for the energy functions into a series of structured linear systems which are easily solvable for the *polynomial coefficients* of the energy functions. Nonlinear controllers are produced as a byproduct, since it is possible to construct controllers based on the energy functions which solve the HJB PDEs. The performance of the controllers is investigated by considering a finite element model for a soft robot mechanical system which exhibits both geometric and material nonlinearity. We compare higher-order polynomial controllers computed using a coarse mesh with lower-order polynomial controllers computed using a fine mesh to see where it is best to invest computational resources.

Nicholas Corbin
University of California San Diego

ncorbin@ucsd.edu

MS2

Approximations of Operator Lyapunov Equations with Applications to Nonlinear Feedback Control

Computing the Lyapunov function of a system plays a crucial role in optimal feedback control, for example when the policy iteration is used. In this talk we will focus on the Lyapunov function of a nonlinear autonomous finite-dimensional dynamical system that we will rewrite as an infinite-dimensional linear system using the Koopman operator. We show that this infinite-dimensional system has the structure of a weak-* continuous semigroup in a specially weighted Lp-space. This allows us to establish a connection between the solution of an operator Lyapunov equation and the desired Lyapunov function. It will be shown, that the solution to this operator equation attains a rapid eigenvalue decay, which we will use to justify finite rank approximations with numerical methods. The usefulness for numerical computations will also be demonstrated with two short examples.

Bernhard Hoeveler
TU Berlin
hoeveler@math.tu-berlin.de

MS2

Nonlinear Balanced Truncation: Computations via Tensor Systems

Nonlinear balanced truncation is a model order reduction technique that reduces the dimension of nonlinear systems on nonlinear manifolds and accounts for either open- or closed-loop observability and controllability aspects of the nonlinear system. Two computational challenges have so far prevented its deployment on large-scale systems: (a) the computation of Hamilton-Jacobi-(Bellman) equations that are needed for characterization of controllability and observability aspects, and (b) efficient model reduction and reduced-order model (ROM) simulation on the resulting nonlinear balanced manifolds. We present a novel unifying and scalable approach to balanced truncation for large-scale systems that consider a Taylor-series based approach to solve a class of parametrized Hamilton-Jacobi-Bellman equations that are at the core of balancing. The specific tensor structure for the coefficients of the Taylor series (tensors themselves) allows for scalability up to thousands of states. Moreover, we will present a nonlinear balance-and-reduce approach that finds a reduced nonlinear state transformation that balances the system properties. The talk will illustrate the strength and scalability of the algorithm on two semi-discretized partial differential equations, namely Burgers' equation and the Kuramoto-Sivashinsky equation.

Boris Kramer
University of California San Diego
bmkramer@ucsd.edu

Jeff Borggaard
Virginia Tech
jborggaard@vt.edu

Serkan Gugercin
Virginia Tech
Department of Mathematics
gugercin@vt.edu

MS3

Robustness of Feedback Control for SIQR Epidemic Model Under Measurement Uncertainty

We study a four state continuous time control system that models susceptible, infected, isolated, and recovered (SIQR) populations in the presence of an infectious disease to which immunity is long lasting, and whose three feedback controls represent isolation, contact regulation, and vaccination. The model contains four time-varying uncertainties. One uncertainty models uncertain immigration into a population. The other three represent uncertainties in the measurements of the susceptible, infected, and isolated population counts that are used in the feedback controls. We study the model using input-to-state stability (ISS), which is a generalization of asymptotic stability that is commonly used in control engineering to quantify the effects of uncertainty, and which coincides with asymptotic stability when the uncertainties are zero. Using a strict Lyapunov function construction method from a recent paper https://doi.org/10.3934/mcrf.2022043 by H. Ito, M. Malisoff, and F. Mazenc, we provide two ISS results that quantify the robustness of the feedback control with respect to the four uncertainties. We illustrate the effectiveness of our approach in simulations, using parameter values from the COVID-19 pandemic.

Summer Atkins
Louisiana State University
srnatkins@lsu.edu

Michael Malisoff
Louisiana State University
Department of Mathematics
malisoff@lsu.edu

MS3

Personalized Optimal Treatment of Alzheimer's Disease

Alzheimer's disease (AD) affects more than 5 million people in the US. Recently, personalized treatment of AD has provided a new way to manage AD patients' treatment plans. Such treatment requires a new approach to analyzing the growing electronic AD brain data. In this talk, we will introduce a mathematical modeling approach to describe the progression of AD clinical biomarkers and also incorporate patient data for personalized prediction and optimal treatment. More specifically, an AD personalized prediction is provided via validating the mathematical model on a multi-institutional dataset of AD biomarkers. Personalized therapeutic simulation studies for AD patients are performed by adding optimal controls to this model.

Wenrui Hao
Pennsylvania State University
wxh64@psu.edu

MS3

Adaptive Feedback Control for Positive Difference Equations with Applications in Pest Management

An adaptive feedback control scheme is proposed for stabilizing a class of forced nonlinear positive difference equations. The adaptive scheme is based on high-gain adaptive controllers, and contains substantial robustness with respect to model uncertainty as well as with respect to persistent forcing signals, including measurement errors. Our motivating application is to pest or weed control, and the theory is illustrated with examples where we analyze potential insect control strategies analytically and numerically.

Richard L. Rebarber
University of Nebraska
rrebarber1@unl.edu

MS3

Optimizing the Dose of a Personalized Neoantigen Cancer Vaccine

In this presentation, I will show how we can formulate a mathematical optimization problem to find the optimal cancer vaccine dose that elicits a sufficient immune response to kill tumor cells, at a fixed vaccination schedule. The optimization problem is subject to a personalized cancer vaccine mathematical model that encompasses the immune response cascade produced by the vaccine in a patient. We performed *in silico* experiments on six patients with advanced melanoma to validate the results of applying an optimal and suboptimal vaccine dose. According to our model simulations, an ideal vaccine dose may dramatically lower tumor sizes in certain patients with less frequent vaccinations but higher vaccine doses on some of the vaccination days.

Wencel W. Valega Mackenzie
U.S. Food and Drug Administration
wvalegam@vols.utk.edu

MS4

Control Theoretic Properties of a Certain Fluid-Structure PDE Interaction

In this talk, we present our recent qualitative results with respect to a coupled partial differential equation (PDE) system which describes a certain fluid-structure interaction (FSI), as it occurs in nature. This particular FSI system comprises a Stokes flow, evolving within a three-dimensional cavity, coupled via a boundary interface, to a two dimensional Euler-Bernoulli or Kirchhoff plate which displaces upon a sufficently smooth bounded open subset of the cavity boundary. Among other items, we discuss the Gevrey regularity properties of the strongly continuous contraction semigroup which models this FSI.

George Avalos
University of Nebraska-Lincoln
Department of Mathematics and Statistics
gavalos2@unl.edu

MS4

Analysis and Control in Poroelastic Systems with Applications to Biomedicine

We answer questions related to tissue biomechanics via well-posedness, sensitivity analysis, and optimal control problems for fluid flows through deformable porous media. These results are relevant for many applications in biology, medicine and bio-engineering, including tissue perfusion, fluid flow inside cartilages and bones, and design of bioartificial organs. We focus on the local description of the problem, which involves implicit, degenerate, nonlinear poroelastic systems, as well as scenarios where the global features of the problem are accounted for through a multi-scale coupling with a lumped circuit.

Lorena Bociu
NC State University
Raleigh, NC
lvbociu@ncsu.edu

MS4

Exponential Synchronization of Kumamoto Oscillators with Time-Delayed Interactions

We study the asymptotic synchronization for the Kuramoto oscillators model with time-delayed interactions. The Kuramoto model appears in many biological/physiological applications. Then, often, time delay effects have to be considered. We provide an explicit lower bound on the coupling strength and an upper bound on the time delay in terms of initial configurations ensuring exponential synchronization. Our approach, which relies on continuity arguments and careful estimates of the trajectories, allows us to significantly relax previous thresholds on the time delay size. We are able to consider both the cases with initial phase diameter less or greater than $\frac{\pi}{2}$.

Chiara Cicolani
Università degli Studi dell'Aquila
chiara.cicolani@graduate.univaq.it

Cristina Pignotti
University of L'Aquila
pignotti@univaq.it

Young-Pil Choi
Yonsei University, Seoul 03722, Republic of Korea
ypchoi@yonsei.ac.kr

MS4

A Kalman Rank Condition for the Controllability of Coupled Stokes Systems

We consider the controllability of a class of systems of n Stokes equations, coupled through terms of order zero and controlled by m distributed controls. Our main result states that such a system is null-controllable if and only if a Kalman type condition is satisfied. This generalizes the case of finite dimensional systems and the case of systems of coupled linear heat equations. The proof of the main result relies on the use of a Kalman operator and on a Carleman estimate for a cascade type system of Stokes equations. Using a fixed-point argument, we also obtain that if the Kalman condition is verified, then the corresponding system of Navier-Stokes equations is locally null-controllable

Luz de Teresa, Yingying Wu-Zhang
UNAM
ldeteresa@im.unam.mx, yyngwu@gmail.com

Takéo Takahashi
INRIA
Institut Élie Cartan de Lorraine
takeo.takahashi@inria.fr

MS5

Navigating the Landscape of Fear

The term Landscape of Fear was coined to describe the impact that the presence of predators (real or perceived) can have on the foraging behavior of prey animals. Much of the work in this area has focused on detailed observational studies of complex spatial environments. At the same time, traditional optimal foraging theory seeks to predict the behavior of foraging animals by modeling them as rational optimizers. However, these models have primarily considered simple, discrete environments due to computational costs. In this talk we take inspiration from both approaches and model optimal foraging as an optimal path-planning problem over a continuous two-dimensional environment and finite time horizon. We allow for detailed spatial variation in the availability of food and prevalence of predators. Furthermore, we use the framework of piecewise-deterministic Markov processes to model predation via random events that affect the dynamics of the prey animal. We consider two possible optimization criteria, each governed by system of Hamilton-Jacobi-Bellman PDEs. Additionally, we present a modified model that approximately accounts for how a prey animal depletes food in its environment, which in general is too computationally expensive to handle exactly in a dynamic programming setting. We close by presenting some numerical experiments, which can be used to generate predicted usage rates for a foraging animal in a synthetic landscape.

Marissa Gee
Center for Applied Mathematics
Cornell University
mag433@cornell.edu

MS5

Efficient and Scalable Algorithms for Curvature Constrained Motion in the Hamilton-Jacobi Formulation

We discuss a Hamilton-Jacobi formulation for optimal trajectory planning, with specific application to curvature constrained motion. Grid-based numerical methods for such problems suffer from the curse of dimensionality, and are thus applicable to models with low dimensional state spaces. We develop models which are amenable to new numerical methods for high dimensional Hamilton-Jacobi equations and circumvent the curse of dimensionality. We discuss the manners in which our models differ from classical control-theoretic formulations, and demonstrate our methods with examples in higher dimensions.

Christian Parkinson, Isabelle Boyle
University of Arizona
chparkin@math.arizona.edu, ijboyle1@arizona.edu

MS5

Time-Optimal Motion Planning with Hamilton-Jacobi-Reachability

With the help of public-available tools like helperOC and optimized_dp, the reach-avoid tube computation of higher dimensions has become accessible, making it possible to design complex systems for solving multi-agent motion planning (MAMP) tasks. The existing approach applying Hamilton-Jacobi (HJ) reachability to multi-agent tasks requires the latest arrival time as a priori. It finds a feasible plan that finishes by the latest arrival time. Such an approach is useful in air traffic control. However, the latest arrival time is unknown in many robotics applications like warehouse management or delivery in the neighbourhood, etc. Specifically, the common objective for these tasks is minimizing the makespan, the arrival time among all tasks. In this talk, we will introduce the Time-Optimal Motion Planning algorithm on top of the HJ reachability solver. The algorithm optimizes the arrival time and iteratively finds the optimal/bounded sub-optimal arrival time. By incorporating the ideas of Prioritized Planning and Priority Based Search, the algorithm can solve MAMP problems with a low makespan. The system can guarantee completeness when the given MAMP problem is well-formed.

Dingyi Sun
Simon Fraser University
dingyi_sun@sfu.ca

MS5

Piecewise-Deterministic Markov Processes in Path-Planning under Uncertainty

Piecewise-deterministic Markov Processes (PDMPs) provide a convenient framework for modeling non-diffusive stochastic perturbations in a planning environment. (E.g., changes in the wind direction when planning a path for a sailboat, changes in robot dynamics due to a partial breakdown, changes in destination and/or domain geometry, changes in priorities of a foraging animal when meeting a predator, etc.) Such stochastic switches are typically modeled through a continuous-time Markov chain on a set of "deterministic modes", with transition probabilities estimated using historical data. This mathematical formalism leads to a system of weakly-coupled PDEs (one for each mode) and additional computational challenges. In this talk we will discuss several notions of optimality and robustness for controlling PDMP models of path planning, focusing on numerical techniques needed to make them practical. [Parts of this presentation reflect joint work with Zhengdi Shen, Dongping Qi, Elliot Cartee, Marissa Gee, Cole Miles, MingYi Wang, and REU students at Cornell University.]

Alexander Vladimirsky
Dept. of Mathematics
Cornell University
vlad@math.cornell.edu

MS6

Stability Properties of the Allen-Cahn Equation and Applications to Optimal Control

In this talk we present results regarding the Lipschitz continuity of the data to solution mapping of the Allen-Cahn equation based on suitable duality and boot-strap arguments. The associated Lipschitz constant depends upon $1/\epsilon$, where $\epsilon << 1$ denotes the parameter that models the thickness of the transition layer. Special care is exercised in order to obtain estimates that do not require additional smoothness on the data and / or severe restrictions on the size of the norm that measures the difference between data. These results are being used in the context of an optimal control problem to develop first and second order necessary and sufficient conditions. In addition, these Lipschitzian stability properties allow us to study the stability of locally optimal solutions with respect to perturbations of initial data.

Konstantinos Chrysafinos
Department of Mathematics
National Technical University of Athens, Greece

chrysafinos@math.ntua.gr

MS6

C0 Interior Penalty Methods for an Elliptic Distributed Optimal Control Problem with General Tracking and Pointwise State Constraints

We consider C^0 interior penalty methods for a linear-quadratic elliptic distributed optimal control problem with pointwise state constraints in two spatial dimensions, where the cost function tracks the state at points, curves and regions of the domain. Error estimates and numerical results that illustrate the performance of the methods are presented.

Zhiyu Tan
Louisiana State University
Center for Computation and Technology
ztan4@lsu.edu

MS6

Optimal Control Problems in Ferromagnetic Shielding

This talk presents recent mathematical results for the optimal control of an H(curl)-quasilinear first kind variational inequality (VI) with a bilateral vector curl-constraint, stemming from the ferromagnetic shielding phenomenon. We propose a tailored regularization approach based on the Helmholtz decomposition and a reduction of the first-order constraint to the zeroth-order one in combination with a smoothed Yosida penalization. In this way, a suitable family of approximating quasilinear variational equalities is obtained. The corresponding limiting analysis not only leads to a well-posedness result for the VI but also reveals its dual formulation. The corresponding optimal control is mainly complicated by the involving H(curl)-quasilinearity, the bilateral vector curl-constraint, and the non-smoothness. On the basis of the proposed regularization, we derive nesessary optimality conditions, including a characterization of the limiting dual multiplier through curl-projection and cut-off type arguments.

Irwin Yousept
University Duisburg-Essen
irwin.yousept@uni-due.de

MS7

Hamilton-Jacobi-Bellman Approach for Optimal Control Problems of Sweeping Processes

This talk is concerned with a state constrained optimal control problem governed by a Moreau's sweeping process with a controlled drift. The focus of this work is on the Bellman approach for an infinite horizon problem. In particular, we focus on the regularity of the value function and on the Hamilton-Jacobi-Bellman equation it satisfies. We discuss a uniqueness result and we make a comparison with standard state constrained optimal control problems to highlight a regularizing effect that the sweeping process induces on the value function.

Cristopher Hermosilla
Universidad Técnica Federico Santa María Chile
cristopher.hermosill@usm.cl

MS7

Lipschitz Property of the Reachable Set for a Class of Perturbed Sweeping Processes

In this talk we summarize the ideas related to the establishment of the Lipschitz property for the reachable set multifunction of a sweeping process with a discontinuous perturbation, and whose moving set is a time dependent enlargement of a fixed convex set. With such purpose, we discuss a preliminary version of a Filippov-type result that allows us to estimate the distance between approximating arcs and the trajectories of the sweeping process under consideration. This leads to the Lipschitz regularity of the associated reachable set and its sensitivity with respect to the initial conditions of the data.

Vinicio R. Rios
Louisiana State University
vrios3@lsu.edu

MS7

Galerkin-Like Method for Integro-Differential Inclusions with Applications to State-Dependent Sweeping Processes

In this paper, we develop the Galerkin-like method to deal with first-order integrodifferential inclusions. Under compactness or monotonicity conditions, we obtain new results for the existence of solutions for this class of problems, which generalize existing results in the literature and give new insights for differential inclusions with an unbounded right-hand side. The effectiveness of the proposed approach is illustrated by providing new results for nonconvex state-dependent integrodifferential sweeping processes, where the right-hand side is unbounded, and the classical theory of differential inclusions is not applicable. It is the first result of this kind. The paper ends with an application to the existence of an optimal control problem governed by an integro-differential inclusion in finite dimensions.

Emilio Vilches
Universidad de O'Higgins
emilio.vilches@uoh.cl

MS8

Overview of the Session; Data-Driven Vertical Stabilization Algorithms in Tokamaks

This presentation is divided in two parts. The first part aims at providing an overview of the topics that will be discussed throughout the mini-symposium. Nuclear fusion reactors are complex systems, characterized by a plethora of challenging modeling and control problems that need to be addressed for safe and efficient operation. In this mini-symposium innovative solutions for some of these problems will be presented. In particular, in the first session plasma control is mainly considered, and issues such as vertical stabilization, plasma shape control and control of the plasma internal profiles are discussed. In the second one, more technology-oriented issues are discussed, such as instrumentation development, high-performance diagnostics, safety systems and remote handling. In the second part of the talk, one of such problems is introduced, namely that of plasma vertical stabilization. Recently, some results have been published that propose novel methods to solve the problem of vertically stabilizing unstable plasmas in a partially or fully data-driven way. These techniques include stabilizing Extremum Seeking, online model identification and control design through Dynamic Mode Decomposition and (Deep) Reinforcement Learning. In this talk an overview of these recent advancements is given.

Adriano Mele
Università degli Studi della Tuscia
Dipartimento di Economia, Ingegneria, Società e Impresa
adriano.mele@unitus.it

Gianmaria De Tommasi
Università degli Studi di Napoli Federico II
detommas@unina.it

Luigi Emanuel Di Grazia
Università della Campania Luigi Vanvitelli
luigiemanuel.digrazia@unicampania.it

Sara Dubbioso, Alfredo Pironti
Università degli Studi di Napoli Federico II
sara.dubbioso@unina.it, pironti@unina.it

MS8

Nonlinear Infinite-Dimensional Regulation of the Safety Factor Profile in Tokamaks with Moving Electron Cyclotron Drives

Tokamaks are torus-shaped devices designed to confine hot-ionized gas (commonly referred to as plasma) using strong magnetic fields. The net magnetic field in the tokamaks must be helical to ensure that the charged particles in the plasma remain within the tokamaks toroidal volume. The pitch of this helical magnetic field is characterized by a plasma property called the safety factor profile. Magnetohydrodynamic studies have shown that maintaining the safety factor profile at the desired level is critical to the stability of the plasma. Conventional controllers designed to maintain the safety factor profile at the desired levels rely on approximating the plasma dynamics. A distributed controller eliminates the need for such finite-dimensional approximation of the safety factor dynamics. However, the infinite-dimensional control law must be translated into physical actuator variables such as the current drive powers and electron-cyclotron deposition locations for practical implementation. This work proposes a nonlinear distributed controller and discusses the steps involved in computing the above-mentioned physical actuator variables from the infinite-dimensional control law. The effectiveness of the controller in a DIII-D tokamak scenario is demonstrated through nonlinear simulations. *Supported by the US DOE (DE-SC0010537 and DE-SC0010661).

Sai Tej Paruchuri
Lehigh University
Mechanical Engineering and Mechanics
saitejp@lehigh.edu

Eugenio Schuster
Mechanical Engineering and Mechanics
Lehigh University
schuster@lehigh.edu

MS8

Model Predictive Control System for Different Phases of Plasma Confinement in DEMO Tokamak

DEMO tokamak must be capable of advanced modes of tokamak operation, hence they need a high performance magnetic control system to keep and to maintain a self-sustaining fusion reaction for long duration. This presentation deals with the use of a model predictive control (MPC) technique to perform the magnetic confinement of a plasma in the DEMO tokamak. By keeping the features of MPC technique, e.g. the controller can take into account the constraints that characterize the normal operations of a nuclear fusion reactor, the controller can be adapted to the different phases, and hence different goals, of the plasma discharge. In the past, others control systems were proposed for DEMO tokamak and their performance was verified to be satisfactory in case of saturation in the actuators. Now via an MPC based approach, control performance can be improved by bringing into account constraints during the design phase of the controller. A validated nonlinear evolution code is used to show the performance of the proposed controller. *This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Gaetano Tartaglione
Università di Napoli Parthenope
Dipartimento di Ingegneria
gaetano.tartaglione@uniparthenope.it

Roberto Ambrosino
DIETI, Università degli Studi di Napoli Federico II, Napoli
roberto.ambrosino@unina.it

Marco Ariola
Dipartimento di Ingegneria, Università di Napoli Parthenope
marco.ariola@uniparthenope.it

Wolfgang Biel
Institut für Energie und Klimaforschung
Forschungszentrum Jülich GmbH, Germany
w.biel@fz-juelich.de

Luigi Di Grazia
Dipartimento di Ingegneria
Università degli Studi della Campania Luigi Vanvitelli
luigiemanuel.digrazia@unicampania.it

Massimiliano Mattei
DIETI, Università degli Studi di Napoli Federico II, Napoli
massimiliano.mattei@unina.it

Adriano Mele
Università degli Studi della Tuscia
Dipartimento di Economia, Ingegneria, Società e Impresa
adriano.mele@unitus.it

MS9

Control of Repairable Systems

One feature of a repairable system is that it can be restored to satisfactory operation by some actions, including parts replacements or changes to adjustable settings. The mathematical model for such systems is governed by distributed parameter systems coupled through an ordinary differential equation. The purpose of this talk is to discuss the exact controllability property of this system. In particular, we show that under an appropriate condition which makes practical sense, one can reduce the repairable system to a finite-dimensional linear system with time delay. Later, we show that this corresponding finite-dimensional linear system with time delay is controllable.

Daniel O. Adu, Weiwei Hu
University of Georgia
daniel.adu@uga.edu, Weiwei.Hu@uga.edu

MS9

Sufficient Conditions for Infinite-Dimensional Differential Algebraic Equations to Generate a Contraction

Infinite-dimensional differential algebraic equations often arise as coupling of partial differential equations where one equation is in equilibrium. Previous work on (E,p)-radiality of infinite-dimensional algebraic equations is used to obtain verifiable conditions for well-posedness of these equations. Furthermore, we have obtained an extension of the Lumer-Phillips generation theorem to differential algebraic systems that guarantees generation of a contraction. The results are illustrated with a number of examples arising from physical applications, such as electro-chemical and reaction-diffusion equations.

Kirsten Morris
Dept. of Applied Mathematics
University of Waterloo
kmorris@uwaterloo.ca

Birgit Jacob
University of Wuppertal, Germany
bjacob@uni-wuppertal.de

MS10

"Computation and Evaluation of Nonlinear Feedback in Fluids"

Feedback control laws for fluid flows are typically linear due to the challenges in approximating the Hamilton-Jacobi-Bellman equations. Grid-based approaches are prohibitive, even when using reduced-order models of modest dimension. However, it has been demonstrated that polynomial approximations can lead to effective nonlinear feedback strategies for nonlinear systems. These have been implemented for polynomial-quadratic regulator problems in the QQR software repository. In this talk, we demonstrate the effectiveness of higher-degree feedback laws on the problem of stabilizing the flow past circular cylinders using cylinder rotation as the actuation mechanism. Interpolatory model reduction and POD will be used to generate reduced-order models for developing control laws. Two test cases, flow past a single cylinder and flow past twin cylinders will be discussed. The improvements in the quadratic regulator cost of quadratic and cubic feedback laws over linear feedback will be presented.

Jeff Borggaard, Ali Bouland
Virginia Tech
jborggaard@vt.edu, bouland@vt.edu

MS10

2D and 3D convective Brinkman-Forchheimer equations perturbed by a subdifferential and applications to control problems

The following convective Brinkman-Forchheimer (CBF) equations (or damped Navier-Stokes (NS) equations) with potential

$$\frac{\partial \boldsymbol{y}}{\partial t}-\mu\Delta\boldsymbol{y}+(\boldsymbol{y}\cdot\nabla)\boldsymbol{y}+\alpha\boldsymbol{y}+\beta|\boldsymbol{y}|^{r-1}\boldsymbol{y}+\nabla p+\Psi(\boldsymbol{y}) \ni \boldsymbol{g}, \nabla\cdot\boldsymbol{y}=0,$$

in a d-dimensional torus is considered, where $d \in \{2,3\}$, $\mu, \alpha, \beta > 0$ and $r \in [1,\infty)$. For $d = 2$ with $r \in [1,\infty)$ and $d = 3$ with $r \in [3,\infty)$ ($2\beta\mu \geq 1$ for $d = r = 3$), we establish the existence of a unique global (local for the case $d = 3$ with $r \in [1,3]$) strong solution for the above multivalued problem with the help of the abstract theory of m-accretive operators. We explored the m-accretivity of the nonlinear as well as multivalued operators, Yosida approximations and their properties, and several higher order energy estimates in the proofs. For $r \in [1,3]$, we quantize the NS nonlinearity $(\boldsymbol{y}\cdot\nabla)\boldsymbol{y}$ to establish the existence and uniqueness results, while for $r \in [3,\infty)$ ($2\beta\mu \geq 1$ for $r = 3$), we handle the NS nonlinearity by the nonlinear damping term $|\boldsymbol{y}|^{r-1}\boldsymbol{y}$. Finally, we discuss the applications of the above developed theory in feedback control problems like flow invariance, time optimal control and stabilization.

Sagar Gautam, Kush Kinra
Indian Institute of Technology Roorkee - IIT Roorkee
India
sagar_g@ma.iitr.ac.in, kkinra@ma.iitr.ac.in

Manil Mohan
Indian Institute of Technology Roorkee - IIT Roorkee
India
maniltmohan@ma.iitr.ac.in

MS10

"Finite Dimensional Model Based Iterative Learning Control Design and CFD Validation for Smart Rotors Deployed on Wind Turbines"

Developments in actuators and sensors have led to considerable interest in their use for aerodynamic load control for wind turbines, thereby increasing power extraction efficiency, including economic competitiveness against other sources of alternative energy. In particular, the route is to embed smart devices into the rotor blades and use them in combination with active control to modify the blade section aerodynamics. The aim is to minimize lift fluctuations due to disturbances. In previous research it has been shown that iterative learning control can be used in this area, where the first reported research used model-free designs. The results obtained demonstrated the basic feasibility of iterative learning control in this application area. This paper uses proper orthogonal decomposition to construct finite-dimensional models from the computational fluid dynamics-based representations of the defining partial differential equations. The performance of the resulting control laws is examined using the computational fluid dynamics representation of the dynamics.

Weronika Nowicka, Bing Chu, Owen Tutty
University of Southampton
wnn1g12@southamptonalumni.ac.uk, b.chu@soton.ac.uk, o.r.tutty@soton.ac.uk

Eric Rogers
University of Southampton
Department of Electronics and Computer Science
etar@ecs.soton.ac.uk

MS10

"Numerical Stabilization of the Boussinesq System

Using Boundary Feedback Control"

The standard model used in fluid dynamics is a set of partial differential equations called Navier-Stokes equations. To describe more complex fluid flow scenarios, it is often coupled with the convection-diffusion equation, which accounts for temperature variation in the flow. The resulting system is known as the Boussinesq equations. Both models are inherently non-linear, and they are frequently used, e.g., for fluid problems that occur naturally in modeling, designing, and controlling energy-efficient building systems. The design of such energy-saving buildings is essential to meet national energy and environmental challenges. The Boussinesq system is unstable and sensitive to noise and disturbances for certain values of its parameters. In this talk, I will discuss our efficient feedback control strategies to numerically stabilize the system. Our strategies optimize energy use in the aircraft or a building by controlling the indoor environment such as temperature, humidity, and air quality.

Ruchi Sandilya
Cornell University
USA
sar4018@med.cornell.edu

MS11

Low-Order LPV Controller for Incompressible Navier-Stokes Equations

This talk presents a learning-based technique for designing a reduced-order LPV controller for incompressible Navier-Stokes equations. The computational challenges in synthesizing a controller design come from the large size of the state space model resulting from Navier-Stokes equations and its inherent quadratic nonlinearities. We present a two-folded model reduction approach tailored to nonlinear controller design for incompressible Navier-Stokes equations and similar PDE models involving quadratic nonlinearities. In the first approximation step, we seek a low-dimensional encoding of the states for replacing the nonlinear terms with a low-dimensional linear parameter varying (LPV) surrogate. We show that this step leads to LPV models that approximate the actual dynamics well even with significantly low dimensional parameter space (less than 10). Thus, the application of standard Linear Matrix Inequalities (LMI) approaches already comes into reach. Nevertheless, another bottleneck remains that the LMI problem grows exponentially with the number of vertices on the parameter space. Therefore, we propose a second layer of approximation that is tailored for the low-order LPV representation to accurately follow the original dynamics with a scalable-sized lower-dimensional model. We illustrate the performance of the proposed reduced-order LPV controller by applying it to the full-order nonlinear Navier-Stokes equations.

Amritam Das
KTH
am.das@tue.nl

MS12

The Effect of Governance Structures on Optimal Control of Two-Patch Epidemic Models

Infectious diseases continue to pose a threat to the health of humans globally. While the pathogen spread transcends geographical boundaries, infectious disease management typically occurs within distinct spatial units, determined by geopolitical boundaries. The allocation of management resources within and across regions (the governance structure) can affect epidemiological outcomes considerably. Policy-makers are often confronted with a choice between applying control measures uniformly or differentially across regions. Here, we investigate the extent to which governance structures affect the costs of an infectious disease outbreak in two-patch systems using an optimal control framework. A uniform policy implements control measures with the same time-varying rate functions across both patches, while these measures are allowed to differ between the patches in a non-uniform policy. We compare results from two systems of differential equations representing the transmission of cholera and Ebola, respectively, to understand the interplay between transmission mode, governance structure, and the optimal control of outbreaks. In our case studies, the governance structure has a meaningful impact on the allocation of resources and the burden of cases, although the difference in total costs is minimal. Understanding how governance structure affects both the optimal control functions and epidemiological outcomes is crucial for effectively managing infectious diseases.

Emily Howerton
Pennsylvania State University
eah394@psu.edu

Kyle Dahlin
Odum School of Ecology, University of Georgia
kydahlin@gmail.com

Christina Edholm
Scripps College
Claremont, CA 91711
cedholm@scrippscollege.edu

Lindsey Fox
Eckerd College
foxl@eckerd.edu

Margaret Reynolds
United States Military Academy, West Point
margaret.reynolds@westpoint.edu

Brandon Hollingsworth
Cornell University

George Lytle
University of Montevallo

Melody Walker
University of Florida
melody.walker@medicine.ufl.edu

Julie Blackwood
Williams College
jcb5@williams.edu

Suzanne M. Lenhart
University of Tennessee
Department of Mathematics
slenhart@utk.edu

MS12

Mathematics of a Single-Locus Model for Assessing the Impacts of Pyrethroid Resistance and Temperature on Population Abundance of Malaria

Mosquitoes

In this study, we developed a novel genetic population deterministic model of nonlinear ordinary differential equations for the temporal dynamics of the immature and adult anopheles mosquito population with sex structure. The deployment of larvicides, pupacides, and adulticides are incorporated into the model. Furthermore, the fitness costs associated with resistance are accounted for, including heterogeneities in fecundity, development rates, and natural mortality rates. The model is used to investigate the spread and management of insecticide resistance in mosquitoes. A threshold for the stability of the insecticide-sensitive-only and insecticide-resistant-only boundary equilibria is derived. Moreover, a conjecture has been established for the stability of the co-existence equilibrium where mosquitoes of all genotypes exist. Furthermore, we show that stratifying the mosquito population by genotype induces a bistability phenomenon. The impact of varying temperatures and insecticide coverage on the mosquito population by genotype in the context of the moderate and high fitness cost scenarios have been explored numerically.

Jemal Mohammed-Awel
Morgan State University
jemal.mohammed-awel@morgan.edu

MS12

Optimal Control Applied to Combination Regimens for Patients with Multiple Myeloma

Multiple myeloma is a type of blood cancer that is not currently curable. There are dozens of therapies used to treat patients with multiple myeloma, which makes it challenging to determine optimal regimens. We developed a mathematical model of tumor-immune dynamics and performed sensitivity analysis to determine the most influential interactions in the model. We used these results to help guide selection of three therapies to combine, and we compared various approaches for optimizing a specified outcome. We showed that a piecewise-constant approximation to an optimal control solution achieves outcomes that are close to optimal, while also being a clinically-feasible regimen.

Mahya Aghaee
Department of Mathematics
University of Florida
mahyaaghaee@ufl.edu

Urszula Ledzewicz
Southern Illinois University, USA
uledzew@siue.edu

Michael Robbins
io904 LLC
mrobbins@io904.org

Natalie Bezman
Pfizer, Inc
nbezman@gmail.com

Hearn Jay Cho
Icahn School of Medicine
Mount Sinai, NY
hearn.jay.cho@mssm.edu

Helen Moore
University of Florida
helen.moore@medicine.ufl.edu

MS12

Structural Instability and Linear Allocation Control in Models of Substance Use Disorder

Substance use disorders (SUDs) are often viewed mathematically as social diseases, where addictive behaviors are assumed to spread through direct social contact between individuals. Modeling SUD strictly as an infectious disease excludes those who develop them through nonsocial means, such as trauma exposure or mental illness. We extend the classic SIS and SIR disease models in context of SUD by incorporating both contact and non-contact routes into substance use. With the inclusion of a non-contact linear addiction rate, the dynamics of the model fundamentally change so that the addiction free equilibrium (AFE) and the basic reproductive number no longer exist. We employ techniques from optimal control to determine the strategies which minimize SUD in a population where an AFE does not exist.

Leigh Pearcy
University of Tennessee, Knoxville
lpearcy1@vols.utk.edu

MS13

Energy Decay of Boundary Coupled Systems Involving Wave Euler-Bernoulli Beam with One Locally Singular Fractional Kelvin-Voigt Damping

In this talk, we investigate the energy decay of hyperbolic systems of wave-wave, wave-Euler- Bernoulli beam and beam-beam types. The two equations are coupled through boundary connection with only one localized nonsmooth fractional Kelvin-Voigt damping. By reformulating the systems into augmented model and by using frequency domain approach, combined with multiplier technique and some interpolation inequalities, we establish different types of polynomial energy decay rate which depends on the order of the fractional derivative and the type of the damped equation in the system.

Ibtissam Issa
Lebanese University
ibtissamissa6@gmail.com

MS13

Null Controllability of a Class of Non-Newtonian Incompressible Viscous Fluids

We investigate the null controllability property of systems that mathematically describe the dynamics of some non-Newtonian incompressible viscous flows. The principal model we study was proposed by O. A.Ladyzhenskaya, although the techniques we develop here apply to other fluids having a shear-dependent viscosity. Taking advantage of the Pontryagin Minimum Principle, we utilize a bootstrapping argument to prove that sufficiently smooth controls to the forced linearized Stokes problem exist, as long as the initial data in turn has enough regularity.

Juan Bautista Limaco Ferrel
Universidade Federal Fluminense

jlimaco@id.uff.br

MS13

Stability in Composite Materials

We report on some new classes of differential equations which are used to describe several applied situations, for instance composite materials. Starting from the description of the model, we will conclude with some stability results for the associated Cauchy problem.

Dimitri Mugnai
Universitta della Tuscia
dimitri.mugnai@unitus.it

Genni Fragnelli
Universita degli Studi di Bari
genni.fragnelli@unitus.it

MS13

Bilinear Control of Degenerate Wave Equations

In this talk I will present a result of bilinear local controllability in finite time $T > 0$ along the ground state for a degenerate wave equation [P. Cannarsa, P. Martinez, C. Urbani, Bilinear control of a degenerate hyperbolic equation, preprint arXiv:2112.00636]. We prove that there exists a threshold time T_0 such that for $T > T_0$ a classical result of local controllability along the ground state can be achieved. For T smaller than T_0, we show that the reachable set from the ground state is contained in a C^1-submanifold of infinite codimension. For $T = T_0$ and strong degeneracy, a classical result of local controllability can be proved, except for a countable set of values of the degeneracy parameter. Finally, for $T = T_0$ and weak degeneracy, the reachable set is a C^1-submanifold of codimension 1. The strategy of the proof consists in the resolution of a moment problem coupled with an inverse mapping theorem. However, because of the degeneracy of our operator, new difficulties with respect to [K. Beauchard, Local controllability and non-controllability for a 1D wave equation with bilinear control, JDE, 250(4), 20642098 (2011)] arise. Indeed, while for $T > T_0$ it suffices applying Ingham theory to solve the moment problem, for $T = T_0$ we need to extend the Kadec 1/4 Theorem and finally, for T smaller than T_0, we combine general results on non-minimal families of exponentials with density properties of the eigenvalues of our degenerate operator.

Cristina Urbani
University of Rome Tor Vergata
urbani@mat.uniroma2.it

MS14

Virtual Maps for Belief Space Planning in GPS-Denied Environments

This talk will present a novel belief space planning framework for GPS-denied mobile robots operating in obstacle-filled environments, reliant upon simultaneous localization and mapping (SLAM) with range sensors. The proposed system comprises path generation, place recognition forecasting, belief propagation and utility evaluation using a virtual map, which estimates the uncertainty associated with map cells throughout a robot's workspace. We evaluate the performance of this framework in simulated experiments, showing that the proposed algorithm maintains a high coverage rate when used for exploring unknown environments, while also maintaining low mapping and localization error. The real-world applicability of our framework is also demonstrated on an underwater remotely operated vehicle (ROV) exploring a harbor environment. We also apply the framework to general belief space planning queries within a completed map, and analyze the benefits of virtual maps as a tool for approximating the outcomes of belief propagation.

Brendan Englot
Stevens Institute of Technology
benglot@stevens.edu

MS14

Sampling-Based Reachability Analysis for Fast and Robust Motion Planning

In this talk I will present a new approach to robust motion planning that leverages recent advances in reachability analysis. Specifically, I will first present a new class of sampling-based forward reachability algorithms that are fast, do not require pre-computations, can account for both aleatoric and epistemic uncertainty, work with nonlinear dynamics, and enjoy surprisingly tight error bounds. Building upon these results, I will present a robust rapidly-exploring random-tree (Robust-RRT) algorithm that tightly integrates forward reachability analysis with sampling-based motion planning. Experimental results on nonlinear, underactuated, and hybrid systems will demonstrate the generality and robustness of our approach.

Marco Pavone
Autonomous Systems Laboratory
Stanford University
pavone@stanford.edu

Thomas Lew
Stanford University
thomas.lew@stanford.edu

MS14

Decentralized Multi-Agent Navigation in Complex Scenarios

Multi-robot systems (MRS) have received significant attention owing to their wide-ranging applications, such as warehouse automation, search and rescue, surveillance, and last-mile delivery. Navigation is an integral part of these applications, which involve the robots moving safely, and efficiently and cooperating with other robots in the MR-Sour research is centered around developing decentralized methods for generating safe and efficient multi-robot navigation. Our research on multi-agent navigation is classified into three parts; In the first part, we present approaches for quadrotor or UAV navigation in multi-agent, complex scenarios and subsequently extend it to handle sensing dynamics constraints and uncertainty. In the second part, we consider dense multi-agent environments, where we propose two methods for navigating ground robots in congested scenes. In the third part, we describe new methods that exploit reinforcement learning (RL) to improve the performance of decentralized navigation. In particular, we present our current approach to multi-agent navigation using inter-agent communication and RL-based navigation.

Dinesh Manocha
University of Maryland, College Park

dmanocha@umd.edu

MS14

Error-Bounded Approximation of Pareto Fronts in Robot Planning Problems

Many problems in robotics seek to simultaneously optimize several competing objectives under constraints. A common approach to solving these multi-objective optimization problems is to create a single cost function made up of the weighted sum of the individual objectives. Solutions to this scalarized optimization problem are Pareto optimal solutions to the original multi-objective problem. However, a key challenge is finding an accurate representation of the Pareto front. Using uniformly spaced weight vectors can be inefficient and does not provide error bounds. Thus, we address the problem of computing a finite set of weight vectors such that for any other weight vector, there exists an element in the set whose error compared to optimal is minimized. We prove fundamental properties of the optimal cost as a function of the weight vector, including its continuity and concavity. Using these properties, we propose an algorithm that greedily adds the weight vector least-represented by the current set, and provide bounds on the error. We demonstrate that our proposed approach significantly outperforms uniformly distributed weights for different robot planning problems with varying numbers of objective functions.

Stephen L. Smith
University of Waterloo
stephen.smith@uwaterloo.ca

MS15

Infinite Horizon Optimal Control for a General Class of Semilinear Parabolic Equations

This talk deals with infinite horizon optimal control problems subject to semilinear parabolic equations. A Neumann boundary control is considered and high nonlinearities in the state equation are allowed. The existence of a solution is proved and first and second order optimality conditions are derived. They are used to analyze the approximation of the infinite horizon problem by finite horizon problems. A key point in this analysis is the proof of boundedness of the states in the infinite horizon cylinder.

Eduardo Casas
Universidad de Cantabria
ETSI Ind y de Telecom
eduardo.casas@unican.es

Karl Kunisch
University of Graz and Radon Institute, Austrian
Academy of
Science, Austria
karl.kunisch@uni-graz.at

MS15

Multidimensional Aspects of the Problem of Deautoconvolution

The talk presents new analytical and numerical results for the inverse problem of deautoconvolution in the multidimensional case with respect to solution uniqueness and ill-posedness. Deautoconvolution means here the reconstruction of a real-valued L^2-function with support in the n-dimensional unit cube from observations of its autoconvolution. Based on multi-dimensional variants of the Titchmarsh convolution theorem, there are proven the twofoldness of solutions in the full data case, and in the limited data case the uniqueness of non-negative solutions, for which the origin belongs to the support. A glimpse of rate results for regularized solutions completes the presentation. This talk presents joint work with Yu Deng (TU Chemnitz) and Frank Werner (University of Wuerzburg). Research is supported by the Deutsche Forschungsgemeinschaft (DFG) under grant HO 1454/13-1.

Bernd Hofmann
TU Chemnitz
Faculty of Mathematics
hofmannb@mathematik.tu-chemnitz.de

MS15

Algebraic Flux Correction (AFC) in Optimal Control

We consider an optimal control problem governed by an elliptic partial differential equation with pointwise state constraints. Boundary layer in the state may occur in particular in the convection dominated case. One observes oscillations in the state if the FE-discretization is not fine enough. In this talk we discuss an algebraic flux correction (AFC) to avoid such undesired effects. This talk is joint work with Jens Baumgartner.

Arnd Roesch
University Duisburg-Essen
arnd.roesch@uni-due.de

MS17

Implementation of Atca Based High-Speed Multichannel Data Acquisition Systems for Magnetic Diagnostics and Plasma Centroid Position Control

Magnetic control enables regulation of plasma position and shape in a tokamak, both directing the plasma to a desired set point and counteracting disturbances to maintain plasma equilibrium. This work presents a new optimal controller for regulating plasma position and shape in ISTTOK tokamak through active control. Using physics concepts and computational tools, the controller provides realtime control of the plasma centroid position, made possible by recent upgrades to the tokamak's real-time plasma control system, the controller successful development relies on the upgraded hardware which integrates magnetic probe signals in real-time.

Lilia Doménica Corona Rivera
Princeton Plasma Physics Laboratory
lcoronar@pppl.gov

Adriano Mele
Università degli Studi della Tuscia
Dipartimento di Economia, Ingegneria, Società e Impresa
adriano.mele@unitus.it

Nuno Cruz
Universidade de Lisboa, Lisboa, Portugal and
Consorzio RFX, Padua, Italy
nunocruz@ipfn.tecnico.ulisboa.pt

Hugo Alves, Bernardo Carvalho, Humberto Figueiredo,
Horacio Fernandes
Universidade de Lisboa, Lisboa, Portugal
halves@ipfn.ist.utl.pt, bernardo.carvalho@tecnico.ulisboa.pt,

fernando@ipfn.tecnico.ulisboa.pt,
hf@ipfn.tecnico.ulisboa.pt

MS17

Instrumentation and Control Developments for Fusion Experiments and High-Performance Diagnostics

New challenges in diagnostics, control and instrumentation arise due to the demanding operating conditions in the ITER project as well as other relevant fusion projects. These include the need for high data acquisition rates, high physical event rates, complex control and diagnostic algorithms. The ability to manage large amounts of data during long experimental pulses is also crucial. Additionally, equipment used must be able to withstand radiation in high magnetic fields as well as neutron irradiation in the fusion device's port cells. Both in-house built prototypes and complete systems were installed in major international fusion experiments and used to test the latest designs. The relevant technologies employed include Advanced Telecommunications Computing Architecture, high speed electronic devices for signal digitization, complex real-time algorithms for physics analysis, control and data compression. The algorithms were implemented to be executed using high-performance computing with field-programmable gate arrays and multicore processor architectures. The teams at IPFN IST Lisbon and at ITER NBTF RFX Padova for instrumentation and control have undertaken several initiatives and international collaborations to create reliable and advanced equipment for monitoring and controlling fusion devices. This presentation will showcase the designs, outcomes and solutions achieved, which have been implemented for various devices such as ITER, JET, SPIDER and IFMIF-DONES.

Nuno Cruz
Universidade de Lisboa, Lisboa, Portugal and
Consorzio RFX, Padua, Italy
nunocruz@ipfn.tecnico.ulisboa.pt

A. J. N. Batista, J. Sousa, B. Gonçalves
Instituto Superior Técnico Universidade de Lisboa
Instituto de Plasmas e Fusão Nuclear
toquim@ipfn.tecnico.ulisboa.pt,
jsousa@ipfn.tecnico.ulisboa.pt,
bruno@ipfn.tecnico.ulisboa.pt

C. Taliercio, G. Manduchi, A. Luchetta
Consorzio RFX
Corso Stati Uniti, 4, 35127 Padova Italy
cesare.taliercio@igi.cnr.it, gabriele.manduchi@igi.cnr.it,
adriano.luchetta@igi.cnr.it

MS17

Modeling and Control of Flexible Manipulators for Nuclear Fusion Applications

The talk will deal with computationally efficient finite element modeling techniques for robots with flexible links. As a matter of fact, manipulators for nuclear fusion applications can be subject to large deflections due to the kinematic configuration they assume within the tokamak and due to the large payloads that they transport. Such deflections need to be accurately predicted in order to avoid damages in the plant. Based on the dynamic behavior of the flexible manipulators, the talk will also deal with control strategies for vibration and oscillation suppression.

Stanislao Grazioso
Università degli Studi di Napoli Federico II
Dipartimento di Ingegneria Industriale
stanislao.grazioso@unina.it

MS17

Shorted Turn Protection (STP) - A Realtime Protection System for NSTX-U Using Generated C++ Code

The National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physics Laboratory suffered a coil failure in the Spring of 2016. The analysis showed that a field coil had degraded, leading to a cooling water leak causing a short-circuit. It was decided to add another protection system, Shorted-Turn-Protection (STP), with the goal of detecting shorted turns in the coils as well as in buswork during machine operation, to prevent further and collateral damage to other nearby components by interdicting during the shot. Based on previous experience on NSTX-U, it was decided to implement STP as a deterministic computer system, using a Real Time Linux variant as OS and C++ as the main development language. The main approach is to compare stepwise modeling results with measured coil voltages and currents to detect inductance changes. It was decided to structure STP to allow the inclusion of algorithms developed with specific tools, like mathematical simulation packages (MatLab/SimuLink etc), using the tools capability to export the algorithm as code to be included into the overall system. This approach allows the use of different skill sets and creates a template for other systems that operate on real time data, such as diagnostic systems. This talk will present the design in detail, describing the software components and how they form a reusable template for processing real time data. This work was supported by US DOE Contract No. DE-AC02-09CH11466.

Frank Hoffman
Princeton Plasma Physics Laboratory
fhoffman@pppl.gov

MS18

Confidence Bands for Evolution Systems Described by Parameter-Dependent Analytic Semigroups

We derive confidence bands for parameter-dependent impulse response functions (IRF) and system outputs as convolutions for evolution systems described by analytic semigroups with regularly dissipative generators in a Gelfand triple of Hilbert spaces. This work is motivated by a diffusion-based forward population model for the transdermal transport of ethanol and the deconvolution of estimates of breath alcohol concentration (BrAC) from biosensor measured transdermal alcohol concentration (TAC). In this application the model parameters depend on covariates that vary across individuals (e.g sex, BMI), the environment (e.g. temperature, humidity) and sensor hardware. Our focus is the study of how parameter uncertainties propagate through the forward model to the TAC signal and back through the inverse to deconvolved estimates of BrAC. The model parameters are assumed to be response variables in linear regression models with the covarites as predictor variables. We use the delta method for nonlinear functions of random vectors with asymptotically normal distribution to obtain estimates for confidence bands for the resulting IRF and system outputs. Our approach relies on the Frechét derivative of the analytic semigroup that describes the evolution of the system. Convergence of approximations and extensions to deconvolved estimates of BrAC from the TAC signal are discussed. Numerical studies demonstrating the efficacy of our approach are presented.

Gary Rosen, Haoxing Liu, Larry Goldstein
Department of Mathematics
University of Southern California
grosen@math.usc.edu, haoxingl@usc.edu, larry@usc.edu

Susan Luczak
Department of Psychology
University of Southern California
luczak@usc.edu

MS18

Optimal Sensor Placement from Empirical Observability for Flexible Wings

By characterizing observability based on the sensitivity of the output energy to changes in initial conditions, we are developing analytical and empirical observability Gramians for a linear model of a cantilevered flat plate. The nonlinear observability, including potential motion coupling, is also considered for a cantilevered plate attached to a freely moving rigid body, mimicking the motion of a flexible airplane wing attached to the fuselage. A sensor placement algorithm is applied to both classes of systems to assess the optimal locations for strain and/or accelerometer sensors based on measures of the observability Gramians. A finite element model is used to generate data and assess the sensor placement strategy as a step towards optimal sensor placement on an airplane wing.

Natalie Brace
University of Washington
nbrace@uw.edu

Nicholas Andrews
Dept. of Aeronautics and Astronautics U. of Washington
nian6018@uw.edu

Jeremy Upsal
Department of Applied Mathematics
University of Washington
jupsal@uw.edu

Kristi Morgansen
Dept. of Aeronautics and Astronautics
U. of Washington
morgansen@aa.washington.edu

MS18

A Note on Controllability and Non-Controllability for a Rayleigh Beam with Piezoelectric Actuator

In this paper, the exact controllability problem for a Rayleigh beam with piezoelectric actuator is considered. The main contributions of this work are to give the exact controllability results and to give the minimal controllability time. Controllability results show that the space of controllable initial data depends on the location of the actuator. The approach to prove controllability results is based on Hilbert Uniqueness Method and some results on the theory of Diophantine approximation. Due to the rotary inertia term in the Rayleigh beam equation, Rayleigh beam equation possesses finite propagation speed, and consequently the controllability results hold when the control time surpasses a critical time. This critical time is proved to be the minimal controllability time by using the Riesz basis property of exponential family in $L^2(0,T)$. The controllability in critical time is still an open problem.

Yubo Bai
Fudan University
ybbai21@m.fudan.edu.cn

Christophe Prieur
CNRS GIPSA-Lab
christophe.prieur@gipsa-lab.fr

Zhiqiang Wang
Fudan University
wzq@fudan.edu.cn

MS19

Local Boundary Feedback Control of the 2D Shallow Water Flow

We address sub-critical shallow water flow regulation problems around a given steady state by means of local boundary conditions. Analyzing the Riemann invariants in a one-dimensional setting, we build stabilizing local boundary conditions that guarantee the stability in L2-norm of the perturbation state. For the viscous case, we use an a priori energy estimate of the perturbation state and the Faedo-Galerkin method, to design a boundary feedback control law for the volumetric flow in a finite time that is prescribed by the solvability of the associated Cauchy problem. We iterate the same approach to build by cascade a stabilizing feedback control law for infinite time. Thanks to a positive arbitrary time dependent stabilization function, the control law provides an exponential decay of the energy. Some numerical results are performed for the controller applied to the nonlinear problem demonstrate the performance of the method.

Ben Dia
King Fahd University of Petroleum and Minerals, Saudi Arabia
Saudi Arabia
ben.dia@kfupm.edu.sa

MS19

Optimal Control of 3-D Compressible Navier-Stokes Equations

he compressible Navier-Stokes equations comprise a system of PDE describing the evolution of a linearly viscous compressible fluid. We consider the general problem of driving fluid to a given state over a fixed time, under the influence of a distributed control in the form of a body force. We first obtain an existence result for optimal controls of the nonlinear system, which relies on augmenting the cost functional in order to exploit a weak-strong uniqueness property to ensure the existence of unique states. We also obtain the first order necessary conditions for a linearized version of the 3d compressible system in the form of a Pontryagin maximum principle that includes state constraints.

Stefan Doboszcz
University of Maryland
USA

sbdoboszczak@smcm.edu

MS19

Practical Aspects of H_∞-Robust Feedback Control of Incompressible Flows

Linearization based controller design for stabilizing a steady state of the Navier-Stokes equations has been thoroughly investigated in theory and proved to work in numerical simulations. In view of applications that come with various sources of model uncertainties, however, standard observer-based controllers are likely to fail because of their inherent lack of robustness. In order to realize a stabilizing control in a simulation, two approximation steps are imminent: the discretization of the continuous states both of the plant and the controller and a computation of the linearization. Both approximations can be arbitrarily close but will always introduce an error in the model used for the controller design. In this work we focus on the linearization error. We introduce a generic boundary control setup, show its wellposedness as an abstract linear system and that a linearization error can be qualified via perturbations in coprime factorizations of the transfer functions. Then, in theory, this source of uncertainty can be compensated through an H_∞ controller design. In view of practical realizations, we briefly address computational issues that come with the design of H_∞-robust controller for large-scale systems and present numerical studies of its robustness both with respect to linearization and to controller dimension reduction errors.

Jan Heiland
Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany
heiland@mpi-magdeburg.mpg.de

Steffen Werner
Courant Institute, New York University
steffen.werner@nyu.edu

Peter Benner
Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany
benner@mpi-magdeburg.mpg.de

MS19

A Cluster-Pod Based Model Reduction Method for Boundary Control of Fluid Flows

Simulation, optimization, and control of large-scale dynamical systems is critical in various domains of science and engineering. A highly efficient and precise model reduction technique is fundamental for real-time control design. Proper orthogonal decomposition (POD) and clustering methods have become widely used in many engineering applications such as geometric modeling, data and image analysis, and numerical partial differential equations. However, POD does not capture the nonlinear characteristics of high dimensional nonlinear systems since it assumes the snapshots belong to a linear vector space. This paper proposes a cluster POD-based reduced-order modeling mathematical formulation where the shortest distance between snapshots is approximated locally by the Euclidean distance. Comprehensive results from the 1D and 2D Burgers equations show that the proposed model reduction technique is more effective and precise than standard POD. A linear quadratic regulator is designed based on the reduced-order model to control the flow and validated on the full-order model of the 2D Burgers equation governing a nonlinear convective flow.

Seddik Djouadi
University of Tennessee at knoxville
Department of Electrical engineering and computer science
mdjouadi@utk.edu

Dan Wilson
University of Tennessee, Knoxville
Department of Electrical Engineering and Computer Science
dwilso81@utk.edu

Tumin Wu
University of Tennessee, Knoxville
twu19@vols.utk.edu,

S. Sahyoun
Emulate Energy
Sweden
s. sahyoun

MS20

Identifiability and Observability of Nonsmooth Input-Output Systems

Identifiability and observability are key properties in the analysis of input-output dynamical and control systems. Identifiability analysis aims to study if the systems parameters can be uniquely determined from the systems output, while observability analysis aims to study if the systems initial states can be uniquely determined from the systems output. To study these properties, many approaches have been developed that can be broadly classified as geometric-based methods and sensitivity-based methods. However, these traditional methods only work for smooth functions, which can be a limitation in many physical phenomena and applications where nonsmoothness is present in the system. Given that the sensitivity-based methods are the less computationally expensive class of methods, hence, amenable to large-scale problems, and in order to overcome the nonsmoothness limitation, a new sensitivity-based method is developed that constructs nonsmooth sensitivity rank condition (SERC), denoted by lexicographic SERC (L-SERC). This was accomplished by introducing a first-order Taylor-like approximation theory based on lexicographic differentiation to directly treat nonsmooth functions. For practical implementations, an algorithm is proposed that determines partial structural identifiability or observability in the nonsmooth setting. These new results, as well as illustrative application in climate modeling will be presented.

Hesham Abdelfattah
Aerospace Engineering and Engineering Mechanics Department
University of Cincinnati
abdelfhm@mail.uc.edu

Sameh Eisa
University of Cincinnati
eisash@ucmail.uc.edu

Peter Stechlinski
Department of Mathematics and Statistics
University of Maine

peter.stechlinski@maine.edu

MS20

New Convex Relaxation Methods for Nontrivial Optimal Control Problems

While some real-world applications exhibit behavior that is fundamentally nonsmooth or discrete, useful numerical methods may also introduce nonsmoothness into problems that are otherwise smooth. One such method is the well-known McCormick relaxation method for generating convex underestimators and concave overestimators of finite compositions of simple ”scientific calculator” operations, for use in reachability analysis and global optimization. This presentation explores recent work that grapples with nonsmooth relaxations arising in new process control contexts. First, we present a new bounding technique for control systems expressed as ordinary differential equations (ODEs); this technique generates effective interval bounds compared to established techniques yet involves solving an auxiliary ODE with nonsmooth Karush-Kuhn-Tucker complementarity functions embedded. Next, we show how a recent ”differentiable McCormick” smoothing procedure combines with Pontryagin’s Minimum Principle to produce particularly tight convex relaxations for nontrivial nonlinear optimal control problems. Numerical examples are presented for illustration.

Kamil A. Khan
McMaster University
kamilkhan@mcmaster.ca

Huiyi Cao
Department of Chemical Engineering
caoh14@mcmaster.ca

MS20

Optimization of Passive Systems via Solving Root-Max Problems

In this talk, we consider a problem that is linked to maximizing the passivity radius of a linear time-invariant dynamical system. In state-space form given by the set of matrices $\mathcal{M} = \{A, B, C, D\}$, a continuous-time system is strictly passive if the eigenvalues of A are in the open left half-plane and the Hermitian part of its transfer function is positive definite on the imaginary axis. The passivity radius tells us the smallest size of perturbation that can be made to matrices in $\mathcal{M}$ such that strict passivity is lost. Here, we discuss how to compute the extremal scalar value Ξ for which a certain parametric system with one real parameter loses strict passivity. This particular quantity is important because the value of the passivity radius of a general system depends upon the value of Ξ, and it allows one to construct certificates for the passivity of parametric passive systems. As it turns out, computing Ξ involves solving a potentially nonsmooth eigenvalue optimization problem in two real variables, which falls in a class of problems that we identify as root-max problems. We propose fast new methods to compute Ξ for continuous- and discrete-time systems by generalizing the Hybrid Expansion-Contraction algorithm to root-max problems, which allows us to compute successively better locally optimal approximations to Ξ with a local quadratic rate of convergence. Our approach also outperforms earlier methods in practice.

Tim Mitchell
Queens College, City University of New York
tim.mitchell@qc.cuny.edu

Paul M. Van Dooren
Department of Mathematical Engineering
Catholic University of Louvain
vandooren.p@gmail.com

MS20

Optimal Control of Nonsmooth Dynamical Systems via Direct Methods

Nonsmoothness can arise in dynamical systems frameworks because of the physical problem being modeled, the need for nonsmooth control, or mathematical techniques that introduce nonsmoothness to aid in simulation/optimization methods. Such nonsmoothness necessitates the development of specialized tools and theory, since conventional methods typically require smoothness assumptions to hold. After reviewing the landscape of nonsmooth/discontinuous/hybrid dynamical systems frameworks, we turn our attention to nonlinear complementarity systems (NCSs), a class of highly nonlinear and nonsmooth systems which finds use in mechanical systems, electrical systems, process engineering, and economics. A computationally-relevant sensitivity theory is established for NCSs that is suitable for solving optimal control problems using a direct approach, i.e., parametrically discretizing the control and applying gradient-based sequential methods to update the parameters. Using lexicographic directional differentiation, a new tool in nonsmooth analysis, generalized derivative information is obtained that characterizes the sensitivity of an objective function with respect to parameters in the NCS system. We highlight similar results for other nonsmooth frameworks, including ODEs and differential-algebraic equations, and how this theory can be specialized to linear complementarity systems and optimization-constrained ODEs.

Peter Stechlinski
Department of Mathematics and Statistics
University of Maine
peter.stechlinski@maine.edu

MS21

The Hegselmann-Krause Model with Attractive-Repulsive Interaction

We analize a Hegselmann-Krause model with time delay and attractive-repulsive interaction. More precisely, we deal with an influence function that is positive, i.e. the particles of the system attract each other, in certain suitable time intervals and negative, i.e. the particles of the system repel each other, in some other time intervals. Compensating for the repulsive interaction among the agents with the good behaviour of the system in the time intervals in which the influence function is positive, we prove the convergence to consensus for the Hegselmann-Krause model with time delay and attractive-repulsive interaction.

Elisa Continelli
Università degli Studi dell’Aquila
elisa.continelli@graduate.univaq.it

Cristina Pignotti
University of L’Aquila

pignotti@univaq.it

MS21

Reconstruction of Degenerate Diffusion Coefficient in a Parabolic Equation

In recent years, degenerate parabolic differential equations have received increasing attention, in view of the important related theoretical analysis and practical applications in particular in climate science. We consider the inverse problem of identification of degenerate diffusion coefficient in a one dimensional parabolic equation by some extra data. Several types of degeneracy are considered. We establish stability and uniqueness results under suitable assumptions. The proofs are based on the techniques widely used in control theory and inverse problems, like energy estimates and global Carleman inequalities. Finally, the theoretical results are satisfactory verified by numerically experiments. The presented work has been performed in collaboration with Piermarco Cannarsa and Masahiro Yamamoto.

Anna Doubova
Universidad de Sevilla
doubova@us.es

MS21

Control Methods in Pest Management

We investigate pest management strategies through the Sterile Insect Technique (SIT). We analyze a suitable control system to model impulsive control strategies and develop a comparative evaluation of their outcomes.

Roberto Guglielmi
University of Waterloo
rguglielmi@uwaterloo.ca

MS22

Optimal Decay Rate and Thorough Numerical Analyses for the Fully Magnetic Piezoelectric Smart Beams

Piezoelectric materials exhibit electric responses to mechanical stress, and mechanical responses to electric stress. The electrostatic and magnetizable PDE models, describing the longitudinal oscillations on the beam, with boundary feedback sensors/actuators are known to have exponentially stable solutions. Firstly, a thorough analysis for the maximal decay rate via the optimal choice of feedback sensor amplifiers is discussed. Next, novel Finite Differences, Finite Elements, and order-reduction-based model reductions for these PDEs are proposed. In certain cases, numerical filtering for the spurious high-frequency modes may be unavoidable. These modes simply causes the loss of uniform gap among the eigenvalues as the discretization parameter tends to zero. The exponential decay of the solutions, mimicking the PDE counterparts, can be retained uniformly. A thorough analysis for the maximal decay rate via the optimal choice of feedback sensor amplifiers and the discretization parameter is discussed. Finally, several interactive numerical tests by Wolfram Demonstrations Projects (WDP) are shared to support our results. These are visualizations of the controlled dynamics of the beam, preserving control-theoretic properties of the PDEs such as observability, controllability, stabilizability. As you move a Demonstration's controls, you see a change in its output that helps you understand the controlled vibrational dynamics with optimal feedback controllers.

Ahmet zkan zer
Western Kentucky University
ozkan.ozer@wku.edu

Ahmet Kaan Aydin
University of Maryland - Baltimore County
aaydin@umbc.edu

Rafi Emran, Jacob Walterman
Western Kentucky University
mdrafias.sadeqibnemran227@topper.wku.edu, jacob.walterman061@topper.wku.edu

MS23

Visibility Based Surveillance-Evasion Games

In this talk I consider a two-player zero-sum game in which the payoff involves the visibility of the players in a domain with obstacles. First, I will present a new approach to analyze the boundary conditions of the associated Hamilton-Jacobi-Isaacs HJI equation. These boundary conditions turn out to be non-trivial, and we can prove that the regularity of the profile of the value function near the boundary is related to the curvature of the obstacles. Then, using a new notion of visibility, I will present suboptimal feedback strategies for the players which can be used to approximate the optimal feedback given by the solution to the HJI equation. The main advantage of using these suboptimal feedback controls is that they are computationally efficient and scalable to the case of multiple players.

Carlos Esteve-Yague
University of Cambridge
ce423@cam.ac.uk

Richard Tsai
Department of Mathematics
University of Texas, Austin
ytsai@math.utexas.edu

MS23

Strategic/Tactical AV Routing Under Lane-Change Uncertainty

Strategic plans (e.g., turn-by-turn directions) and tactical plans (e.g., lane change maneuvers) are crucial to safe, comfortable, and effective operation of fully-autonomous and semi-autonomous vehicles. Integrating these strategic and tactical decisions can be challenging since one needs to account for the inherent uncertainty in the outcome of tactical maneuvers. One such approach was recently suggested by Jones, Haas-Heger, and van den Berg, making a distinction between tentative and forced/deterministic lane changes and showing that a Dijkstra-like method is applicable for their specific model. We generalize this approach using the framework of Opportunistically Stochastic Shortest Path (OSSP) problems to encode multiple levels (or even a continuous spectrum) of urgency in lane change maneuvers. We develop broad sufficient conditions to guarantee the applicability of fast label-setting algorithms (such as Dijkstras and Dials) to OSSP and illustrate our method on a variety of road networks.

Mallory Gaspard
Center for Applied Mathematics
Cornell University
meg375@cornell.edu

Alex Vladimirsky
Cornell University
vladimirsky@cornell.edu

MS23

Lane-Level Route Planning for Autonomous Vehicles

We present an algorithm that, given a representation of a road network in lane-level detail, computes a route that minimizes the expected cost to reach a given destination. In doing so, our algorithm solves for the complex trade-offs encountered when trying to decide not just which roads to follow, but also when to change between the lanes making up these roads, in order to - for example - reduce the likelihood of missing a left exit while not unnecessarily driving in the left-most lane. This routing problem can naturally be formulated as a Markov Decision Process (MDP), in which lane change actions have stochastic outcomes. However, MDPs are known to be time-consuming to solve in general. We show that - under reasonable assumptions - we can use a Dijkstra-like approach to solve this stochastic problem, and benefit from its efficient O(n log n) running time. This enables an autonomous vehicle to exhibit natural lane-selection behavior as it efficiently plans an optimal route to its destination.

Jur van den Berg
Waabi
jurvandenberg@gmail.com

MS24

Brain-Inspired Universal Architectures for Progressive Machine Learning: A Systems and Control Perspective

The One Learning Algorithm Hypothesis summarizes strong experimental evidence that the human brain processes visual, acoustic, and haptic signals, for perception and cognition with a workflow that corresponds to the same abstract architectural model. We present our most recent results on the development and performance evaluation of a universal machine learning architecture inspired by this hypothesis. The abstract architecture proposed is comprised by a multi-resolution processing front, followed by a feature extractor, followed by two local learning modules (first an unsupervised one, followed by a supervised one), followed by a deterministic annealing module. There are two global feedback loops, one to the multiresolution processor and one to the feature extractor. Innovative analytical methods and results include: multi-resolution hierarchy, use of Bregman divergences as dissimilarity measures, multi-scale stochastic approximation, multi-scale approximation to Bayes decision surfaces, optimization-information duality. We demonstrate the superior performance and characteristics of the resulting algorithms including: domain agnostic, on-line progressive learning, interpretability, robustness to noise and adversarial attacks, computable performance-complexity tradeoff. We present several applications in signal processing, estimation and control.

John S. Baras
Univ. Maryland
College Park
BARAS@UMD.EDU

MS24

Mathematical Methods for Detection of Epileptiform Activity in EEG of Traumatic Injury Patients

The Epilepsy Bioinformatics Study for Antiepileptogenic Therapy (EpiBioS4Rx), is a multi-site, international collaboration including a parallel study of humans and an animal model, collecting MRI, EEG, and blood samples. The development of epilepsy after traumatic brain injury (TBI) is a multifactorial process and crosses multiple modalities. Without a full understanding of the underlying biological effects, there are currently no cures for epilepsy. We have built a centralized data archive that will allow the broader research community to access these shared data in addition to analytic tools to identify and validate biomarkers of epileptogenesis in imaging and electrophysiology. We have been developing novel mathematical methods for detecting epileptiform activity in EEG that could lead to identifying biomarkers of epileptogenesis. One of these tools that we have developed is Unsupervised Diffusion Component Analysis, which is a novel approach based on the diffusion mapping framework that reduces data dimensionality and provides pattern recognition that can be used to distinguish different states of the patient, such as seizures and non-seizure spikes in the EEG. These manifold learning approaches have shown to be a promising tool to identify potential biomarkers of epileptogenesis that can lead to effective treatments for patients at risk of developing epilepsy.

Dominique Duncan
University of Southern California
duncand@usc.edu

MS24

Feasibility Guarantees for Control Barrier Functions: Theory and Applications

It has been shown that satisfying state and control constraints while optimizing quadratic costs subject to desired (sets of) state convergence for affine control systems can be reduced to a sequence of quadratic programs (QPs) by using Control Barrier Functions (CBFs) and Control Lyapunov Functions(CLFs). One of the main challenges in this approach is ensuring the feasibility of these QPs, especially under tight control bounds and safety constraints of high relative degree. The talk is to provide sufficient conditions for guaranteed feasibility. The sufficient conditions are captured by a single constraint that is enforced by a CBF, which is added to the QPs such that their feasibility is always guaranteed. The additional constraint is designed to be always compatible with the existing constraints, therefore, it cannot make a feasible set of constraints infeasible it can only increase the overall feasibility. We illustrate the effectiveness of the proposed approach on adaptive cruise control and traffic merging problems.

Wei Xiao
MIT
weixy@mit.edu

MS24

Deep Filtering

This talk is about a new deep-learning framework for general nonlinear filtering. Our main focus is on a computationally feasible procedure. The proposed algorithms have the capability of dealing with challenging (infinitely dimensional) filtering problems involving diffusions with randomly varying switching. First, we convert it to a problem in a finite-dimensional setting by approximating the optimal weights of a neural network. Then we construct a stochastic gradient-type procedure to approximate the neural network weight parameters and develop another recursion for adaptively approximating the optimal learning rate. The convergence of the combined approximation algorithms is obtained using stochastic averaging and martingale methods under suitable conditions. Robustness analysis of the approximation to the network parameters with the adaptive learning rate is also dealt with. We demonstrate the efficiency of the algorithm using highly nonlinear dynamic system examples.

Qing Zhang
University of Georgia
Department of Mathematics
qz@uga.edu

George Yin
University of Connecticut, Storrs
gyin@uconn.edu

MS26

Classical and Quantum Control on Graphs

We consider the dynamics and control of nonlinear classical and quantum systems on networks and graphs. In particular we analyze how the graphical structure is useful for elucidating the possible kinds of dynamics that can occur and what control is possible. We also consider the extension to hypergraphs and the relationship to the dynamics of systems described by tensors.

Anthony M. Bloch
University of Michigan
Department of Mathematics
abloch@umich.edu

MS26

On the Compatibility of the Rotating Wave Approximation and the Adiabatic Theory

A two level quantum system driven by one external field can be seen as a left-invariant control system on SU(2) with one control. Such system is deeply studied in the physics literature. Usually it is controlled by using chirped pulses that are obtained using the rotating wave approximation and the adiabatic approximation in cascade. This is done in particular when the resonance frequency is not known precisely (hence when results of ensemble controllability are needed). Both approximations need relatively long time and are based on averaging theory of dynamical systems. Unfortunately, the two approximations cannot be done independently since, in a sense, the two time scales interact. Using techniques of geometric control theory, we study how the cascade of the two approximations can be justified, while preserving the robustness of the adiabatic strategy. Our first result, based on high-order averaging techniques, gives a precise quantification of the uncertainty interval of the resonance frequency for which the population inversion works. As a by-product, we prove controllability of an ensemble of spin systems by a single real-valued control, providing an extension of a celebrated result with two controls by Khaneja, Li, Beauchard, Coron, Rouchon.

Ugo Boscain
Sorbonne Université
ugo.boscain@sorbonne-universite.fr

Mario Sigalotti
INRIA, Centre de Recherche Nancy - Grand Est
mario.sigalotti@inria.fr

Nicolas Augier
LAAS, CNRS
naugier@laas.fr

Remi Robin
Inria, Paris
remi.robin@inria.fr

MS26

Dynamical Decomposition and Subspace Controllability of Networks of Quantum Systems with Symmetries

In the presence of a group of symmetries, the underlying Hilbert space of a network of quantum systems splits into a set of invariant subspaces. The associate control problem becomes the problem of control in parallel of a sequence of quantum systems and in appropriate coordinates the system takes a block diagonal form. The subspace controllability property refers to the situation where some or all of the subsystems is controllable. In this talk we shall present techniques to obtain the change of coordinates that gives such block diagonal form. These are an application, extension and reinterpretation of classical results on the theory of angular momentum, Schur-Weyl duality and Clebsch-Gordan theorem on the decomposition of tensor products representations. We shall consider several examples in detail, and prove the subspace controllability property. Furthermore, we shall show how, in several cases, states in different invariant subspaces have different entanglement properties. For example, in the case of a symmetric network of three quantum bits, the invariant subspaces of dimension 2 contains all vector with distributed entanglement equal to zero. These results pose the general question of the interplay between representation theoretic decompositions of the underlying Hilbert space of a composite quantum system and the entanglement between its different parts.

Domenico D'Alessandro
Department of Mathematics, Iowa State University
daless@iastate.edu

MS26

Control and Stabilization of Mechanical Systems with Symmetry-Breaking Nonholonomic Constraints

We consider mechanical systems on Lie groups whose symmetry is broken by an external potential force (such as gravity) as well as nonholonomic constraints. A motivating example is a simple model for a figure skater called a pendulum skate. We show how the broken symmetry is recovered by introducing advected parameters. The recovery of symmetry helps us reduce the equations of motion to a set of Euler–Poincaré type equations on a vector space. We apply the method of Controlled Lagrangians to the reduced equations to stabilize (relative) equilibria of such systems.

Tomoki Ohsawa, Jorge Silva Garcia
The University of Texas at Dallas
tomoki@utdallas.edu, jorge.garcia4@utdallas.edu

MS27

Real-Time Evacuation Using Adaptive Learning of Unknown Fields

This work deals with the real time estimation of spatially varying fields that are used to model hazardous environments. Assuming the accumulated amount of substances affect the ability of an evacuee, the objective is to design paths that guide an evacuee from the interior to an escape exit in minimum time and with the accumulated amount inhaled below certain thresholds. Since the field is not known, a path-planning scheme cannot be realized. Using the fact that at a given time, the evacuee obtains a spatial measurement, the proposed estimation scheme views the evacuee as a mobile sensor. Due to the motion of the sensor, the field measurement becomes time varying. Such a time-varying sensor is employed to estimate the field using adaptive techniques. When the adaptive scheme provides the current estimate of the field, this estimate is used to guide the mobile sensor to safety. Adding a realistic situation, it is further assumed that each cycle is decomposed into the planning and execution stages. In the planning stage the mobile sensor does not move but still obtains spatial measurements that are used by the adaptive scheme. In this stage the local planning for the path selected is obtained till the next cycle. Simulation results depicting the motion of a mobile sensor in an indoor environment is included to show that an adaptive-based scheme can result in reduced accumulated amounts of the harmful field than that of a straight-path using line-of-sight guidance.

Michael A. Demetriou
Worcester Polytechnic Institute
mdemetri@wpi.edu

MS27

Optimal Control and Shape Optimization for Stokes Flow

We consider the simultaneous optimal control and shape design of a duct which contains a fluid governed by the Stokes equations with mixed boundary conditions. The domain is assumed to be nonsmooth, perturbations are allowed only on the walls, and the control is distributed on the domain. The objective functional is associated to minimize head loss and to enforce a uniform velocity profile at the outlet. We show existence of solutions to the problem and establish a descent algorithm to identify the optimal control-shape pair.

Carlos Rautenberg
George Mason University
crautenb@gmu.edu

Weiwei Hu
University of Georgia
Weiwei.Hu@uga.edu

Andrea Ceretani
University of Buenos Aires - CONICET
aceretani@dm.uba.ar

MS28

Mitigating Extremely Rare Risks in Reinforcement Learning

Mitigating risks constitutes an important objective under the context of robust decision making based on reinforcement learning. This talk introduces techniques for dealing with extremely rare risk events in reinforcement learning as such events may lead to catastrophic consequences. Due to the low frequency of occurrence of these events, it is challenging for data driven methods to model such risky events. Specifically, we present two complimentary approaches to properly account for extremely rare risky events. First, we model the extreme values of the state action value function distribution as parameterized distributions using the extreme value theory (EVT) so as to combat the low frequency occurrence problem. We demonstrate the benefit of using such parameterized distributions by contrasting against other risk averse algorithms. Second, we consider the inherent stochasticity of the reward distribution to better represent the extreme values of the state action value distribution. We experimentally demonstrate the merits of the proposed approach by extensively comparing it with other related works.

Karthik S. N. S.
University of California, Santa Barbara
karthi@ucsb.edu

Yu Wang
University of California Santa Barbara
yu95@umail.ucsb.edu

Peng Li
University of California, Santa Barbara
lip@ucsb.edu

MS29

Control-Affine Extremum Seeking Control with Attenuating Oscillations: A Lie Bracket Estimation Approach

Control-affine Extremum Seeking Control (ESC) systems have been increasingly studied and applied in the last decade. In a recent effort, many control-affine ESC structures have been generalized in a unifying class and their stability was analyzed. However, guaranteeing vanishing control input at the extremum point for said class requires strong conditions that may not be feasible or easy to check/design by the user, especially when the gradient of the objective function is unknown. In this paper, we introduce a control-affine ESC structure that remedies this problem such that: (i) its oscillations attenuate structurally via a novel application of a geometric-based Kalman filter and a Lie bracket estimation approach; and (ii) its stability is characterized by a time-dependent (one-bound) condition that is easier to check, for example, via simulations and relaxed when compared to the generalized approach mentioned earlier. We provide numerical simulations of three problems to demonstrate the effectiveness of our proposed ESC; these problems cannot be solved with vanishing oscillations using the generalized approach in literature.

Sameh Eisa, Sameer Pokhrel
University of Cincinnati

eisash@ucmail.uc.edu, pokhresr@mail.uc.edu

MS29

Estimation of Rigid Body Inertia Properties with Slosh Dynamics on Special Euclidean Group

In this research, a UKF algorithm is developed on the special Euclidean group of rigid body motion (SE(3)) and its tangent bundle for the estimation of the states and inertia properties, i.e. mass, moment of inertia, and center of mass, in a rigid body with slosh dynamics. The slosh dynamics model is obtained from a classical mechanical model and the natural frequency and damping ratio of each slosh mode is obtained from the measurement data. Rigid body motion formalism in SE(3) helps avoid encountering singularity, non-uniqueness issues, chattering in the presence of noise or delay, and discontinuous control, while it also allows for the design of a single control law for both dynamics of orbital and attitude motions. This methodology is implemented in a spacecraft dynamics scenario, where a mapping from body frame to the actuators' frame may be used to compute the motion in the presence of a variety of known excitation torques from thrusters and thruster locations to demonstrate that the framework is able to produce realistic ideal outputs over the breadth of realistic, ideal thruster and slosh inputs. The accuracy of the approach is determined by comparing it to the true state and quantifying its benefits. The real-world application of the SE(3) formulation in this research would pave the way for rapid advancement in the near future of space missions when robust autonomous controllers are needed in situations where translational and rotational dynamics are coupled.

Morad Nazari, Brennan McCann
Embry-Riddle Aeronautical University
nazarim@erau.edu, mccannb4@my.erau.edu

Matthew Wittal
NASA KSC and Embry-Riddle Aeronautical University
matthew.m.wittal@nasa.gov

Marco Fagetti
Embry-Riddle Aeronautical University
fagettim@my.erau.edu

Jeffrey Smith
Deep Space Logistics, NASA Kennedy Space Center
jeffrey.d.smith@nasa.gov

MS29

Overview on Nonlinear Geometric Controllability with Application to Extremum Seeking Characterization of Soaring Birds Optimized Flight Physics

For centuries, soaring birds, such as albatrosses and eagles, have been mysterious and intriguing for biologists, physicists, engineers, and applied mathematicians. These fascinating biological organisms have the ability to fly for long-duration while spending little to no energy. This flight technique is called dynamic soaring (DS). For biologists and physicists, the DS phenomenon is nothing but a wonder of the very elegant ability of the bird's interaction with nature, and for the engineering community, it is a source of inspiration and an unequivocal promising chance for biomimicking. In literature, mathematical characterization of the DS phenomenon has been limited to optimal control configurations that utilized developments in numerical optimization algorithms along with control methods to identify the optimal DS trajectory taken by the bird/mimicking system. In this paper, we provide a novel two-layered mathematical approach to characterize, model, mimic, and control DS in a simple and real-time implementation. The first layer will be a differential geometric control formulation and analysis of the DS problem. The second layer will be a linkage between the DS philosophy and a class of dynamical control systems known as extremum seeking systems. We believe our framework captures more of the biological behavior of soaring birds and opens the door for geometric control theory and extremum seeking systems to be utilized in systems biology and natural phenomena.

Sameer Pokhrel, Sameh Eisa
University of Cincinnati
pokhresr@mail.uc.edu, eisash@ucmail.uc.edu

MS29

Lie Brackets for Families of Non-Smooth Vector Fields

The Lie bracket of two vector fields X, Y, which in any system of coordinates is defined as

$$x \mapsto [X,Y](x) := DY(x)\cdot X(x) - DX(x)\cdot Y(x),$$

measures the non-commutativity of X's and Y's flows. Clearly, the differentiability of X and Y at any point x is a minimal regularity assumption for pointwise defining the Lie bracket $[X,Y]$. However, flows'commutativity is perfectly meaningful as soon as the involved vector fields just allow for unique solutions of the corresponding Cauchy problems. Now, on the one hand, the standard regularity hypothesis implying such uniqueness is the Lipschitz continuity of the vector field. On the other hand, it is not possible to define everywhere the Lie bracket $[X,Y]$ of two Lipschitz continuous vector fields X, Y. In 2001 H. Sussmann and I introduced the following notion of set-valued Lie bracket for Lipschitz continuous vector fields X and Y:

$$x \mapsto [X,Y]_{set}(x) := co\left\{ v \quad = \quad \lim_{x_k\to x}[X,Y](x_k), \right.$$
$$\left. (x_k)_{k\in\mathbb{N}} \subset Diff(X)\cap Diff(Y) \right\}$$

($Diff(\Phi)$ denotes the set of differentiability points of a function Φ). Basic results such as the commutativity test, Frobenius Theorem, Chow-Rashewski Theorem, etc, still hold with this bracket. Furthermore, applications to higher-order non-smooth Maximum Principles have been proved recently.

Franco Rampazzo
Universita di Padova
Dipartimento di Matematica
rampazzo@math.unipd.it

MS30

Multiplicative Controllability for a Class of Energy Balance Climate Models (EBCM)

In this conference we present some results concerning the multiplicative controllability of degenerate parabolic equations with application to the Energy Balance Climate Models (EBCM).

Giuseppe Floridia
Sapienza Università di Roma

giuseppe.floridia@uniroma1.it

MS30

Consensus Estimates for Opinion Formation Models with On-Off Interaction

We study a Hegselmann-Krause opinion formation model possibly, to make the model more realistic, in the presence of time delay effects. The influence coefficients among the agents are nonnegative, as usual, but they can also degenerate. This includes, e.g., the case of on-off interaction, namely the agents do not communicate in some time intervals. We give sufficient conditions ensuring that consensus is achieved for all initial configurations. Moreover, we analyze the continuity type equation obtained as the mean-field limit of the particle model when the number of agents goes to infinity. Since the estimates for the ODEs system are independent of the agents number, we can extend the consensus estimate to the related PDE.

Cristina Pignotti
University of L'Aquila
pignotti@univaq.it

Elisa Continelli
Università degli Studi dell'Aquila
elisa.continelli@graduate.univaq.it

MS30

The Tragedy of the Commons via Travelling Waves in Mean-Field Games

The main topic of the talk is to observe mathematically the tragedy of the commons in spatial models. Garret Hardin, in 1968, exposed in his seminal paper, several situations in which the uncoordinated action of selfish individuals can lead to the depletion of a common resource, the so-called tragedy of the commons. We will consider a population model that consists of the most basic reaction-diffusion equations and we will formulate a harvesting game. Making use of a mean-field game (MFG) formulation, we will observe how the MFG "reversed" travelling wave solutions in the sense that, in the absence of players the population would invade the whole domain but in the aforementioned Nash equilibria the population gets extinguished. We will also briefly discuss other population models in which this situation arises.

Domenec Ruiz-Balet
Imperial College London
d.ruiz-i-balet@imperial.ac.uk

MS31

Monge-Kantorovich Optimal Transport Through Constrictions and Flow-Rate Constraints

We consider the classical Monge-Kantorovich optimal transport problem with the added constraint that mass is required to pass through constriction points (tolls) with a bounded flow rate. The basic transport problem is motivated by the problem to transport resources/mass between end-point distributions (supply and demand). In this work, we modify the basic problem for the case the transportation cost is quadratic so that the transportation plan abides by flow-rate constraints at specified points. Thus, a "constriction," conceptualized as a toll station, only limits the flow rate across. The key idea is to quantify flow-rate constraints via a bound on a to-be-determined probability density of the times that mass-elements cross toll stations. We cast the transportation scheduling in a Kantorovich framework, leading to a (generalized) multi-marginal transport problem a problem of considerable interest in modern-day machine learning literature.

Anqi Dong
University of California, Irvine
anqid2@uci.edu

MS31

Neural Schrdinger Bridge for Minimum Effort Stochastic Control of Colloidal Self-Assembly

Colloidal self-assembly is a process by which discrete components (e.g., micro-/nano-particles in solution) organize into an ordered state. It enables precision materials synthesis for manufacturing highly-ordered crystalline structures in a cost-effective manner. However, colloidal self-assembly is an inherently stochastic process prone to kinetic arrest due to particle Brownian motion which leads to variability in manufacturing and possibly high defect rates. Thus the need for feedback control to modulate the thermodynamic and kinetic driving forces that govern colloidal self-assembly, has come to the fore. In this talk, we will report our recent works on formulating and solving the finite horizon stochastic optimal control problem for colloidal self-assembly in the space of probability density functions (PDFs) of the underlying state variables. From a control viewpoint, this is a control non-affine instance of the Schrdinger bridge problem - a stochastic dynamic version of the optimal mass transport. We use data-driven representations to numerically solve a system of three coupled PDEs with boundary conditions on the endpoint joint PDFs in the space of order parameters. Our numerical solution involves training a novel physics-informed neural network where the endpoint joint PDF losses are penalized via Sinkhorn divergence. This is joint work with Iman Nodozi and Charlie Yan at UC Santa Cruz, and with Jared O'Leary, Mira Khare and Ali Mesbah at UC Berkeley.

Abhishek Halder
University of California, Santa Cruz
ahalder@ucsc.edu

MS31

Solving Potential Multi-Species Mean Field Games Using Generalized Multimarginal Optimal Transport with Graph-Structured Cost

Optimal transport has seen rapid development over the last decades, recently in particular with a focus on computational methods for numerically solving the problem. The most well-known algorithm is the Sinkhorn algorithm, in which the transport plan is iteratively updated so that its marginal projections match the given marginals. In this talk we show how the ideas behind the Sinkhorn algorithm can be used to derive an algorithm for solving generalized multimarginal optimal transport problems with graph-structured costs, and how this algorithm can be used to solve potential multi-species mean field games. More precisely, in the multimarginal optimal transport problem, an extension of the classical bimarginal problem, a transport plan between several given marginals is sought. In the generalized problem, the fixed given marginals are replaced by convex penalty functions on the marginal and bimarginal projections. We derive a convergent algorithm for such generalized problems based on coordinate ascent in the dual problem, and show how the graph-structure of the underlying transport cost can be utilized to efficiently compute the needed projections of the transport plan. The latter is essential in the algorithm, since a nave computation of the projections scales exponentially in the number of marginals. Finally, we show how potential multi-species mean field games can be cast as a convex graph-structured tensor optimization of this form, and hence solved with this algorithm.

Axel Ringh
Chalmers University of Technology
axelri@chalmers.se

Isabel Haasler
École Polytechnique Fédérale de Lausanne, Switzerland
haasler@kth.se

Yongxin Chen
Georgia tech
yongchen@gatech.edu

Johan Karlsson
Department of Mathematics
KTH Royal Institute of Technology
johan.karlsson@math.kth.se

MS31

Gromov-Wasserstein Discrepancies and Global Optimization for a Class of QAPs

The Gromov-Wasserstein problem is a generalization of the optimal transport problem and is to find the assignment between two sets that preserve pairwise distances to as large degree as possible. This can be used, for example, to quantify how similar two formations or shapes are. Gromov-Wasserstein distances and discrepancies can be formulated as quadratic assignment problems which are in general NP-hard. In this presentation we will discuss recent work on global optimality for a certain class of such problems. In particular, we show that a certain class of Gromov-Wasserstein problems can be formulated as quadratic assignment problems for which the global solution can be found efficiently. The approach is based on reformulating the problem as a low dimensional quadratic problem with convex feasible set. We take a starting point in shrinking approximate covers, linear relaxations and mixed integer strategies which are suitable for this certain problem class. We discuss problem areas where popular methods fail to find near global optima, and where our proposed method can reduce stability issues and provide good bases for decisions when the distance is used for comparative analysis. Finally, we apply the approach on symmetrical and near symmetrical problems which are of special interest in biology.

Martin Ryner
KTH Royal Institute of Technology and Vironova
martinrr@kth.se

Jan Kronqvist
KTH Royal Institute of Technology
jankr@kth.se

Johan Karlsson
Department of Mathematics
KTH Royal Institute of Technology
johan.karlsson@math.kth.se

MS32

Stability Properties of Homogeneous Polynomial Dynamical Systems

In this talk, we provide a system-theoretic treatment of certain continuous-time homogeneous polynomial dynamical systems (HPDS) via tensor algebra. In particular, if a system of homogeneous polynomial differential equations can be represented by an orthogonally decomposable (odeco) tensor, we can construct its explicit solution by exploiting tensor Z-eigenvalues and Z-eigenvectors. We refer to such HPDS as odeco HPDS. By utilizing the form of the explicit solution, we are able to discuss the stability properties of an odeco HPDS. We illustrate that the Z- eigenvalues of the corresponding dynamic tensor can be used to establish necessary and sufficient stability conditions, similar to these from linear systems theory. In addition, we are able to obtain the complete solution to an odeco HPDS with constant control. Finally, we establish results which enable one to determine if a general HPDS can be transformed to or approximated by an odeco HPDS, where the previous results can be applied. We demonstrate our framework with numerical examples.

Can Chen
University of Michigan, Ann Arbor
canc@umich.edu

MS32

Observability of Hypergraphs

In this paper, we develop observability condition for uniform hypergraphs via polynomial control systems theory. Hypergraphs are generalizations of graphs in which edges may connect any number of nodes, thereby representing multi-way relationships which are ubiquitous in many real-world networks including neuroscience, social networks, and bioinformatics. We define a canonical multilinear dynamical system with linear outputs on uniform hypergraphs which captures such multi-way interactions and results in a homogeneous polynomial system. We derive a Kalman-rank-like condition for assessing the local nonlinear observability of this resulting system. We also propose an efficient heuristic to determine the minimum number of observable nodes (MON) needed to achieve local observability and demonstrate our approach numerically on different hypergraph topologies.

Joshua Pickard
University of Michigan
jpic@umich.edu

Amit Surana
Autonomous & Intelligent Systems
Raytheon Tecnologies Research Center
amit.surana@rtx.com

Anthony M. Bloch
University of Michigan
Department of Mathematics
abloch@umich.edu

Indika Rajapakse
University of Michigan
Computational Medicine & Bioinformatics, Mathematics

indikar@umich.edu

MS32

Bridging the Gap Between Safety and Real-Time Control Using Reachable Sets

Autonomous systems offer the promise of providing greater safety and access. However, this positive impact will only be achieved if the underlying algorithms that control such systems can be certified to behave robustly. This talk describes a technique called Reachability-based Trajectory Design, which constructs a parameterized representation of the forward reachable set that it then uses in concert with predictions to enable real-time, certified, collision checking. This approach, which is guaranteed to generate not-at-fault behavior, is demonstrated across a variety of different real-world platforms including ground vehicles, manipulators, and walking robots.

Ram Vasudevan
University of Michigan
ramv@umich.edu

MS32

Equilibrium Control Design in Mean Field Games

In this talk, we analyze an N-player game and the corresponding mean field game with discrete state space. Instead of working under monotonicity conditions, here we consider an anti-monotone running cost. We show that the nonlinear mean field equation may have multiple solutions by solving it using characteristic curves. We also prove that although multiple solutions exist, only the one coming from the entropy solution is charged.

Xin Zhang
Department of Mathematics
University of Vienna
xin.zhang@univie.ac.at

MS33

Some Prediction Results for Rosenblatt Processes and Related Processes

Prediction for stochastic processes has a wide applicability for stochastic models of dynamical systems describing problems of estimation and control as well as other areas. Some processes are described for problems of prediction that include Rosenblatt processes and Gauss-Volterra processes. Rosenblatt processes are a family of processes defined by double Wiener-Itô integrals and Gauss-Volterra processes are a natural generalization of fractional Brownian motions. A stochastic calculus is available for Rosenblatt processes that includes stochastic integration and a change of variables formula. The prediction problems can arise in a variety of stochastic problems. It has been verified empirically that the noise in stochastic control systems is seldom modeled effectively by Brownian motions. The processes described here can be a useful alternative.

Tyrone E. Duncan
University of Kansas
Department of Mathematics
duncan@ku.edu

MS33

Multiple-Time-Scale Nonlinear Output Feedback Control of High Performance Aircraft

The Geometric Singular Perturbation theory (Fenichel, 1979) is a powerful control law development tool for multiple-timescale systems because it provides physical insight into the evolution of the states in more than one timescale. The behaviour of the full-order system can be approximated by the slow subsystem, provided that the fast states can be stabilised on an equilibrium manifold. The fast subsystem describes how the fast states evolve from their initial conditions to their equilibrium trajectory or the manifold. This presentation develops two nonlinear, multiple-time-scale, output feedback tracking controllers for a class of nonlinear, nonstandard systems with slow and fast states, slow and fast actuators, and model uncertainties. The class of systems is motivated by aircraft with uncertain inertias, control derivatives, engine time-constant, and without direct measurement of angle-of-attack and sideslip angle. Each controller is synthesized using timescale separation, lower-order reduced subsystems, and estimates of unknown parameters and unmeasured states. The update laws are so chosen that errors remain ultimately bounded for the full-order system. The controllers are simulated on a nonlinear, six-degree-of-freedom, F-16A Fighting Falcon model performing a demanding combined maneuver. The slow state tracker accomplishes the maneuver with less control effort, while the simultaneous slow and fast state tracker does so with a smaller number of gains to tune.

John Valasek
Department of Aerospace Engineering
Texas A&M University
valasek@tamu.edu

MS33

Neural Network Approaches for High-Dimensional Optimal Control

This talk presents recent advances in neural network approaches for approximating the value function of high-dimensional control problems. A core challenge of the training process is that the value function estimate and the relevant parts of the state space (those likely to be visited by optimal policies) need to be discovered. We show how insights from optimal control theory can be leveraged to achieve these goals. To focus the sampling on relevant states during neural network training, we use the Pontryagin maximum principle (PMP) to obtain the optimal controls for the current value function estimate. Our approaches can handle both stochastic and deterministic control problems. Our training loss consists of a weighted sum of the objective functional of the control problem and penalty terms that enforce the HJB equations along the sampled trajectories. Importantly, training is self-supervised, in that, it does not require solutions of the control problem. We will present several numerical experiments for deterministic and stochastic problems with state dimensions of about 100 and compare our methods to existing approaches.

Deepanshu Verma
Emory University
dverma4@emory.edu

Lars Ruthotto
Departments of Mathematics and Computer Science
Emory University
lruthotto@emory.edu

Xingjian Li
Emory University
xingjian.li@emory.edu

MS33

Unique Continuation Properties (UCP) for Uniform Stabilization of Dynamic Fluid by Feedback Controllers

In dealing with uniform stabilization of parabolic problems near an unstable equilibrium solution, the first critical step of what has become a standard strategy is to ascertain, if possible, Kalman's controllability condition of the projected finite dimensional unstable component. It was discovered about 15 years ago that this property is equivalent to establishing Unique Continuation Properties (UCPs) for the adjoint suitably over-determined eigen-problem. In this talk, with focus on 2D-3D-Boussinesq systems (coupling the N-S with a diffusion equation), several UCPs of the adjoint systems are established to achieve the desired controllability results. These include the required UCPs for the localized interior as well as the localized boundary-based uniform stabilization of an unstable Boussinesq-system. We will also go through the idea of the proof, which follows the pointwise Carleman-type estimates approach.

Roberto Triggiani
University of Memphis
rtrggani@memphis.edu

Xiang Wan
Loyola University Chicago
xwan1@luc.edu

MS34

Turbulent Solutions of Fluid Equations

In the past couple of decades, mathematical fluid dynamics has been highlighted by numerous constructions of solutions to fluid equations that exhibit pathological or wild behavior. These include the loss of the energy balance, non-uniqueness, singularity formation, and dissipation anomaly. Interesting from the mathematical point of view, providing counterexamples to various well-posedness results in supercritical spaces, such constructions are becoming more and more relevant from the physical point of view as well. Indeed, a fundamental physical property of turbulent flows is the existence of the energy cascade. Conjectured by Kolmogorov, it has been observed both experimentally and numerically, but had been difficult to produce analytically. In this talk I will overview new developments in discovering not only pathological mathematically, but also physically realistic solutions of fluid equations.

Alexey Cheskidov
University of Illinois Chicago
acheskid@uic.edu

MS34

The Relativistic Euler Equations with a Physical Vacuum Boundary

We consider the relativistic Euler equations with a physical vacuum boundary and an equation of state $p(\varrho) = \varrho^\gamma$, $\gamma > 1$. We establish the following results. (i) local well-posedness in the Hadamard sense, i.e., local existence, uniqueness, and continuous dependence on the data; (ii) low regularity solutions: our uniqueness result holds at the level of Lipschitz velocity and density, while our rough solutions, obtained as unique limits of smooth solutions, have regularity only a half derivative above scaling; (iii) stability: our uniqueness in fact follows from a more general result, namely, we show that a certain nonlinear functional that tracks the distance between two solutions (in part by measuring the distance between their respective boundaries) is propagated by the flow; (iv) we establish sharp, essentially scale invariant energy estimates for solutions; (v) we establish a sharp continuation criterion, at the level of scaling, showing that solutions can be continued as long as the velocity is in $L^1_t Lip_x$ and a suitable weighted version of the density is at the same regularity level. This is joint work with Mihaela Ifrim and Daniel Tataru.

Marcelo M. Disconzi
Vanderbilt University
marcelo.disconzi@vanderbilt.edu

MS34

Analysis of a Structural Acoustics Model Influenced by Competing Nonlinear Forces

In this talk, I will discuss a structural acoustics model consisting of a semilinear wave equation defined on a 3D bounded domain which is strongly coupled with a Berger plate equation acting on the elastic wall, namely, a flat portion of the boundary. The system is influenced by several competing forces, including boundary and interior source and damping terms. We stress that the power-type source term acting on the wave equation is allowed to have a supercritical exponent, in the sense that its associated Nemytskii operators is not locally Lipschitz from H^1 into L^2. I will present several results on the energy decay, and the blow-up of weak solutions by assuming different assumptions on damping and source terms. The most significant challenge in this work arises from the coupling of the wave and plate equations on the elastic wall.

Yanqiu Guo
Florida International University
yanguo@fiu.edu

MS34

On the Composite Structure Fluid Interaction PDE Models

In this work, we address composite structure-fluid interaction (FSI) systems, where the coupling of the 3D fluid (blood flow) and 3D elastic (structural vascular wall) PDE components is realized via an additional 2D elastic system on the boundary interface. Our main goal is to show the semigroup wellposedness of the corresponding interactive PDE system by way of nonstandard elimination of associated pressure terms via appropriate nonlocal operators and subsequent Babuska-Brezzi formulations. In this regard, we initially formulate an appropriate and nonstandard mixed variational problem for this composite structure-fluid interaction PDE model. The solution to this saddle point problem establishes the semigroup wellposedness of the PDE system under consideration.

Pelin Guven Geredeli
Iowa State University
peling@iastate.edu

MS35

Controllability of Quantum Systems with Rela-

tively Bounded Control Potentials

We study the regularity of solutions of bilinear quantum systems of the type $\dot{x} = (A+u(t)B)x$ where the state x belongs to some complex infinite dimensional Hilbert space, the (possibly unbounded) linear operators A and B are skew-adjoint and the control u is a real valued function of bounded variations. Under suitable regularity assumptions on the operators A and B, it is possible to extend the definition of solution for BV controls and infer continuity of the propagators. While the regularity of the propagators represents an obstacle to exact controllability, on the other hand it is used to present fine estimates on the convergence of finite dimensional approximation schemes. We will then prove exact controllability in projections for bilinear quantum systems with piecewise constant controls taking only two values. As a consequence we extend approximate controllability results to linear quantum systems of the type $\dot{x} = -iH(u(t))x$ with nonlinear dependence on the control.

Nabile Boussaid
Department de Mathematiques
Universite de Franche Comte
nabile.boussaid@univ-fcomte.fr

Marco Caponigro
Universita' di Roma 2, Italy
caponigro@mat.uniroma2.it

Thomas Chambrion
Institut mathématique de Bourgogne
Université Bourgogne
thomas.chambrion@u-bourgogne.fr

MS35

Small-Time Bilinear Control of PDEs via Infinite-Dimensional Lie Brackets

We study some small-time controllability properties of bilinear evolution equations of the form

$$\frac{d\psi(t)}{dt} = \left(\mathcal{A} + \sum_{j=1}^{m} u_j(t)\mathcal{B}_j\right)\psi(t), \quad \psi(0) = \psi_0 \in X$$

where the state ψ evolves in a Banach space X, the controls u_j are real locally integrable functions, $\mathcal{A}$ is an unbounded operator (the drift) and the $\mathcal{B}_j$ are bounded controlled operators on X. These equations are considered, e.g., for the control of quantum systems and population dynamics. We present the following three results:

- for the **Schrdinger equation** on the two-dimensional sphere, small-time approximate controllability holds between couples of particular eigenfunctions of Δ (joint work with T.Chambrion);
- for the **heat equation** on a torus of arbitrary dimension, small-time approximate controllability holds between any two states with the same sign (joint work with A.Duca and C.Urbani);
- for the **wave equation** on a torus of arbitrary dimension (where the state is given by the wave profile and its velocity), small-time global approximate controllability of the velocity holds.

We also describe the main idea behind the proofs (common to all the three results) which is an explicit infinite-dimensional geometric control strategy in terms of opposite Dirac impulsions with a very large magnitude and with a very short time delay.

Eugenio Pozzoli
Universita' di Padova, Italy
epozzoli@math.unipd.it

MS35

Ensemble Optimal Control: ResNets, Diffeomorphisms Approximation and Autoencoders

A few years ago it was observed that Residual Neural Networks (ResNets) can be interpreted as discretizations of control systems, and this fact has been being a valuable tool for the mathematical understanding of Machine Learning. Indeed, this parallelism has been exploited to study existing architectures and to develop new ones. In particular, in this seminar we investigate ResNets obtained from linear-control systems [2]. Despite their simplicity, recent theoretical results obtained with Lie algebraic methods guarantee that they could be surprisingly expressive [1]. We first focus on the problem of approximating a diffeomorphism after observing its action on a finite ensemble of points (the dataset). In this framework, the training of the ResNet corresponds to the resolution of a proper ensemble optimal control problem. In the second part (based on an ongoing work with C. Cipriani) we adapt this machinery to construct an autoencoder: given a manifold M embedded in $\mathbb{R}^n$ and an integer $k < n$, an autoencoder consists of two mappings $\phi : \mathbb{R}^n \to \mathbb{R}^k$ (the encoder) and $\psi : \mathbb{R}^k \to \mathbb{R}^n$ (the decoder) such that $\psi \circ \phi$ is the identity when restricted to M. [1] A. Agrachev, A. Sarychev. Control in the spaces of ensembles of points. SIAM J Control Optim, 2020 [2] A. Scagliotti. Deep Learning approximation of diffeomorphisms via linear-control systems. Math. Control Rel. Fields, 2022

Alessandro Scagliotti
Technical University Munich, Germany
scag@ma.tum.de

MS35

On Affine Equivalence of Sub-Riemannian Metrics on Step 2 Distributions

The classical result of Eisenhart states that if a Riemannian metric g admits a Riemannian metric that is not constantly proportional to g and has the same (parameterized) geodesics as g in a neighborhood of a given point, then g is a direct product of two Riemannian metrics in this neighborhood. We extend this result to sub-Riemannian metrics on a class of step 2 distributions. This is joint work with Zaifeng Lin.

Igor Zelenko
Department of Mathematics
Texas A&M Univerisity College
zelenko@math.tamu.edu

Lin Zaifeng
Texas A&M University
linzf@tamu.edu

MS36

Non-Intrusive Machine Learning Models of PDEs with Differentiable Programming: An Inter-

pretability Study

Surrogate models of partial differential equations (PDEs) are an important area of research for applications where rapid, accurate predictions are desired with low computational costs. Deep learning is a popular approach, but they typically lack the strong physical constraints intrinsic in PDEs. Differentiable programming is an emerging paradigm that aims to enable the expressivity of neural networks inside PDEs, such that the learned model is intimately connected to the physics of the problem by construction. Recent efforts in differentiable programming, such as Neural ODEs, have shown promise in learning accurate parameterizations from simulation data with known numerical properties. However, several earth/climate applications have incomplete or partially known PDEs that need non-intrusive parameterization from observational training data. This leads to a significantly challenging learning problem, where the strengths and weaknesses of differentiable programming are less known. Furthermore, PDEs often exhibit highly nonlinear, chaotic or non-local dynamics, which are harder to model than the local dynamics seen in several canonical PDEs. In this work, we systematically study differentiable programming-based strategies to learn such dynamics with differentiable programming in Neural PDEs. Additionally, we investigate the properties of the learned surrogate PDEs, including their sensitivity to system noise, external forcing, impact on prediction accuracy, and comment on potential applications. Our results show that differentiable programming as a paradigm can accurately model PDEs while surpassing vanilla neural networks. Interestingly, it succeeds even when strong assumptions are made about the missing physics while requiring lesser data and computational cost. However, we also discover that the problem specification and numerical methods employed have a non-trivial impact on the quality and stability of the learned surrogate model, with significant implications for various applications.

Arvind T. Mohan
Los Alamos National Laboratory
arvindm@lanl.gov

MS36

Recent Advances in Continual Learning

Continual learning (CL) plays a key role in dynamic systems in order to adapt to new tasks, while preserving previous knowledge. Most existing CL approaches focus on learning new knowledge in a supervised manner, while leaving the data gathering phase to the novelty detection (ND) algorithm. Such presumption limits the practical usage where new data needs to be quickly learned without being labeled. In this paper, we propose a unified approach of CL and ND, in which each new class of the out-of-distribution (ODD) data is first detected and then added to previous knowledge. Our method has three unique features: (1) a unified framework seamlessly tackling both ND and CL problems; (2) a self-supervised method for model adaptation, without the requirement of new data annotation; (3) batch-mode data feeding that maximizes the separation of new knowledge vs. previous learning, which in turn enables high accuracy in continual learning. By learning one class at each step, the new method achieves robust continual learning and consistently outperforms state-of-the-art CL methods in the single-head evaluation on MNIST, CIFAR-10, CIFAR-100 and TinyImageNet datasets.

Jingbo Sun
Arizona State University
jsun127@asu.edu

MS36

Autonf: Automated Architecture Optimization of Normalizing Flows with Unconstrained Continuous Relaxation Admitting Optimal Discrete Solution

Normalizing flows (NF) are a powerful probabilistic modeling technique that is built upon invertible neural networks. However, developing an efficient flow model that is both powerful and computationally efficient remains a challenge. Existing methods rely on empirical fine-tuning over a large design space, and introducing neural architecture search (NAS) to NF has been limited by the invertibility constraint of NF. In this paper, we present AutoNF, the first automated NF architectural optimization framework that overcomes these challenges. AutoNF uses a new mixture distribution formulation that enables efficient differentiable architecture search for flow models without violating the invertibility constraint. Additionally, AutoNF converts the original NP-hard combinatorial NF architectural optimization problem to an unconstrained continuous relaxation, allowing the discrete optimal architectural solution to be obtained without the loss of optimality due to binarization. We evaluate AutoNF using various density estimation datasets and demonstrate its superior performance-cost trade-offs compared to existing hand-crafted baselines. Our work provides a promising direction for the development of efficient and powerful normalizing flows with automated neural architecture search.

Yu Wang
University of California Santa Barbara
yu95@umail.ucsb.edu

MS37

Control Metastatic Tumor Growth: from Modeling to Numerical Results

Cancer is the second most common global cause of death [WHO, Cancer, 2023]. Modeling metastatic tumor growth with treatment is of paramount importance in developing and advancing knowledge about curing cancer. It is also important to introduce efficient numerical methods to solve the introduced models. In this talk I will present a metastatic tumor growth model, that takes into consideration the control of the disease by assuming different types of treatment, and an efficient numerical method for its resolution. One possible approach to model metastatic tumor growth, including also the treatment, is via a coupled size-structured partial differential equation and a system of ordinary differential equations, the first one describing the evolution in time and size of the metastatic density and the second one describing the evolution in time of the sizes of the primary and secondary tumors, respectively, [K. Iwata, K. Kawasaki, N. Shigesada, A dynamical model for the growth and size distribution of multiple metastatic tumors, J. theor. Biol., 2000]. The proposed approach is derived from the McKendrick/Von Foster transport equation, with a non-local boundary condition, well known in structured population models, [A.G. MKendrick, Applications of mathematics to medical problems, Proceedings of the Edinburgh Math. Society, 1925], [H. von Foerster, Some remarks on changing populations, in: J.F. Stohlman (Ed.), The Kinetics of Cellular Proliferation Grune and Stratton, 1959].

Iulia Martina Bulai
University of Sassari

imbulai@uniss.it

Maria Carmela De Bonis, Concetta Laurita
University of Basilicata
mariacarmela.debonis@unibas.it, concetta.laurita@unibas.it

MS37

Engineering Synthetic Genetic Controllers: from Design to Experimental Build

Engineering artificial gene regulatory networks (synthetic circuits) and metabolic pathways in living cells has many applications across healthcare, industrial biotechnology and environmental science. However, engineering such systems is complicated by high degrees of nonlinearity, lack of modularity, stochasticity and poor robustness (Barajas & Del Vecchio, Curr. Opin. Biotech., 78, 102837, 2022). Feedback control provides a means to overcome these issues, facilitating construction and increasing system performance. Here, we consider the breakdown of modularity as a case study. Non-regulatory interactions emerge in synthetic circuits due to feedback between the circuit and wider host physiology. These interactions perturb the hosts homeostasis leading to changes in metabolism and gene expression which benefit neither engineered processes nor growth. We propose dynamic whole cell design frameworks which capture key host-mediated feedbacks (microbial growth, metabolic interplays and gene expression constraints) (Kim et al., under review; Darlington et al., Nat. Commun., 9, 695, 2018) and show how these interactions complicate (or even simplify) system design. We demonstrate the use of these frameworks in designing autonomous (within cell) feedback controllers which enhance modularity and improve engineered pathway performance. We review how such systems are constructed in living cells and highlight open questions in engineering biology where feedback may provide a solution.

Alexander Darlington
University of Warwick
a.darlington.1@warwick.ac.uk

MS37

A General Approach for Modeling and Design of Physiological Control Systems

Physiological control systems, from the nano- to the macroscale, exhibit some similarities in their dynamical behavior, that can be explained by the implementation of common control strategies. Here, we propose a general framework to describe the fundamental dynamics of physiological systems in order to maintain the homeostatic equilibrium: we devise a simple model of two antagonist states implementing a negative feedback loop; we show that the resulting 2-state negative feedback control system is capable of reproducing the adaptive dynamics of several systems at different scales (Montefusco et al, In EHB 2022). Different from standard engineering control systems, the devised model works without requiring an error detection mechanism (by measuring an external reference signal and deviation from this); indeed, in physiological control systems the reference signal is missing. In addition, the two antagonist states are, at the same time, cause and effect of the behavior of each other, and then it is difficult to distinguish between the process (i.e. plant) to be controlled and the regulatory component (i.e. controller): the control action is embedded in the system itself. For the proposed model, we find new theoretical results by providing a sufficient condition for the existence of an equilibrium point that, in some case of interest, is to be unique and exponentially stable: this equilibrium point is strictly related to the maintenance of the homeostatic balance for a process.

Francesco Montefusco
University of Naples Parthenope
francesco.montefusco@uniparthenope.it

Francesco Amato
Università degli Studi di Napoli Federico II
framato@unina.it

MS37

Modeling of Biomolecular Feedback Control Circuits Through Chemical Reaction Networks

Synergistic cooperation between systems and synthetic biology enables the development of robust biomolecular feedback control circuits (BFCC) that can satisfy clinical and research requirements. In this context, Chemical Reaction Networks (CRNs) represent an appropriate method for providing a simple representation of biological processes, elaborating the information, and extracting new knowledge. Several studies demonstrate the benefits of using CRNs to design BFCC. Starting from the fundamental modules of a biomolecular control circuit, like the molecular subtractor proposed by Cosentino et al (IEEE TAC 2016), it is possible to devise more complex systems, such as the one presented by Sawlekar et al (IEEE TNB 2016) and consisting of a higher modular quasi-sliding mode feedback controller. However, despite the advantages of adopting this modeling framework, several challenges remain to be addressed (e.g., the complexity and uncertainty quantification). Here, we explore CRNs for BFCC design, from the simplest modules to the most complex circuits, including the main applications and software, and highlighting their pros and cons; in particular, we design a potential CRN for modeling and implementing the 2-state negative feedback control system, proposed in this minisymposium, representing a general framework to describe the adaptive dynamics of physiological control systems at different scales (Montefusco et al, In EHB 2022).

Anna Procopio, Carlo Cosentino
University Magna Graecia of Catanzaro
anna.procopio@unicz.it, carlo.cosentino@unicz.it

Francesco Montefusco
University of Naples Parthenope
francesco.montefusco@uniparthenope.it

MS39

Approximation of Compositional Functions With Relu Neural Networks

The power of deep neural network has been successfully demonstrated on a wide variety of high-dimensional problems that cannot be solved by conventional control design methods. These successes also uncover some fundamental and pressing challenges in understanding the representability of deep neural networks for complex and high dimensional input-output relations. Towards the goal of understanding these fundamental questions, we applied an algebraic framework developed in our previous work to analyze ReLU neural network approximation of compositional functions. We prove that for Lipschitz continuous functions, ReLU neural networks have an approximation error upper bound that is a polynomial of the network's complexity and the compositional features. If the compositional features do not increase exponentially with dimension, which is the case in many applications, the complexity of the deep neural network has a polynomial growth. In addition to function approximations, we also establish ReLU network approximation results for the trajectories of control systems, and for a Lyapunov function that characterizes the domain of attraction. The polynomial error upper bound is exemplified using an example of learning a Lyapunov function of a dynamical system that has a nonconvex domain of attraction.

Qi Gong
University of California, Santa Cruz
qigong@soe.ucsc.edu

Wei Kang
Naval Postgraduate School
Department of Applied Mathematics
wkang@nps.edu

Fariba Fahroo
Air Force Office of Scientific Research
fariba.fahroo@us.af.mil

MS39

State Estimation Using a Recurrent Neural Network

While it is well-known that a Kalman filter is an optimal state estimator of linear systems(given Gaussian noises), optimal estimation of non-linear systems of ordinary differential equations is an open problem. In this talk, we will discuss some first steps on a pathway to optimal state estimation using neural networks. We propose to use a recurrent neural network(RNN) to estimate the state of a system. Our codes will be tested on a number of examples, including the Lorenz attractor. The performance of the neural network based estimator will be compared to the popular extended Kalman filter(EKF).

Avneet Kaur
Dept. of Applied Mathematics
University of Waterloo
a93kaur@uwaterloo.ca

MS39

Neural Lyapunov Control with Stability Guarantees

Learning for control of dynamical systems with formal guarantees remains a challenging task. In this talk, we introduce a learning framework to simultaneously stabilize an unknown nonlinear system with a neural controller and learn a neural Lyapunov function to certify a region of attraction for the closed-loop system. The algorithmic structure consists of two neural networks and a satisfiability modulo theories (SMT) solver. The first neural network is responsible for learning the unknown dynamics. The second neural network aims to identify a valid Lyapunov function and a provably stabilizing nonlinear controller. The SMT solver then verifies that the candidate Lyapunov function indeed satisfies the Lyapunov conditions. We provide theoretical guarantees of the proposed learning framework in terms of the closed-loop stability for the unknown nonlinear system. We illustrate the effectiveness of the approach with a set of numerical experiments.

Ruikun Zhou, Thanin Quartz
University of Waterloo
ruikun.zhou@uwaterloo.ca, tquartz@uwaterloo.ca

Hans De Sterck
University of Waterloo, Canada
hdesterck@uwaterloo.ca

Jun Liu
University of Waterloo
j.liu@uwaterloo.ca

MS40

Energy Management for Hybrid Electric Aircraft Propulsion Systems Using Safe Reinforcement Learning with Control Barrier Functions (CBFs)

The aviation industry accounts for about 2% of global human-made CO2 emissions. Efforts are underway to reduce these emissions through the development of more environmentally friendly aviation technologies. Hybrid-electric propulsion, which uses turbo-electric powertrains, is one promising solution to achieve this ambitious goal. In this project, we present a deep reinforcement learning-based energy management strategy to optimize energy efficiency in hybrid electric aircrafts. The goal is to determine the optimal power split between the power demanded from the gas turbine and electric motor components. Both series and parallel configurations are evaluated. The fuel consumption over a flight path is minimized while considering safety constraints on the battery, electric motor, and gas turbine. The proposed strategy leverages learning-based control barrier functions to enforce constraints and ensure safety. To learn these safety certificates, safe trajectories generated by an expert are used to train the safety certificates. An example of such expert trajectories are trajectories that remain confined in feasible set with baseline control performance. The proposed approach is based on optimization and offers safety guarantees under specific assumptions about the smoothness of the dynamical system. Numerical results of the study are presented for both series and parallel configurations and compared to available state-of-the-art results like nonlinear model predictive control.

Yasir Al-Nadawi
Raytheon Technologies Research Center (RTRC)
Raytheon Technologies Research Center (RTRC)
yasir.al-nadawi@rtc.com

MS40

Conflict-Aware Safe Learning-Enabled Control

Safety assurance plays an important role in the successful and widespread deployment of safety-critical systems. However, safety is a bare minimum requirement for safety-critical systems. Many safety-critical systems are also performance-critical systems for which a control design must not only satisfy safety constraints but also deliver a desirable closed-loop behavior with acceptable performance. When safety and performance are of concern, a popular approach that has gained a surge of attention is to blend a control barrier function with a control Lyapunov function (CLF) by solving a quadratic program (QP). However, the QP-based approaches are functions of current states, and we need to solve the optimization problem at every time. Once the conflict occurs between safety and performance, the QP algorithm relaxes the stability by adding a relaxation factor. However, inappropriate selection of the CLF might result in significant conflicts between safety and stability, which in turn requires increasing the magnitude of the relaxation factor to resolve conflicts. This, however, can compromise the convergence of trajectories to the equilibrium point. To address these issues, we presented a data-driven approach to maximize the region over which the conflict between safety and optimality is resolved in the presence of disturbance. The proposed approach can greatly improve the performance of the safe reinforcement learning algorithm.

Bahare Kiumarsi
Michigan State University
kiumarsi@msu.edu

MS40

Control of Connected Automated Vehicles with Event-Triggered Control Barrier Functions

We address the problem of controlling Connected and Automated Vehicles (CAVs) in conflict areas of a traffic network subject to hard safety constraints. It has been shown that such problems can be solved through a combination of tractable optimal control problem formulations and the use of Control Barrier Functions (CBFs) that guarantee the satisfaction of all constraints. These solutions can be reduced to a sequence of Quadratic Programs (QPs) which are efficiently solved on-line over discrete time steps. However, the feasibility of each such QP cannot be guaranteed over every time step. To overcome this limitation, an event-triggered approach is introduced such that the next QP is triggered by properly defined events. In the event-triggering scheme, given the system state at the start of a given QP instance, events are defined associated with the states of CAVs reaching a certain bound, at which point the next QP instance is triggered. We show that the proposed framework eliminates infeasible cases due to time-driven inter-sampling effects, thus also eliminating the need for selecting the size of time steps.

Ehsan Sabouni
Boston University
ehsansabooni2014@gmail.com

Christos G. Cassandras
Division of Systems Engineering
Boston University
mailto:cgc@bu.edu

Wei Xiao
Massachusetts Institute of Technology
mailto:weixy@mit.edu

Nader Meskin
Electrical Engineering Department
Qatar University, Doha, Qatar
nader.meskin@qu.edu.qa

MS40

BarrierNet: Differentiable Control Barrier Functions for Learning of Safe Robot Control

Many safety-critical applications of neural networks, such as robotic control, require safety guarantees. This paper introduces a method for ensuring the safety of learned models for control using differentiable Control Barrier Functions (dCBFs). dCBFs are end-to-end trainable and guarantee safety. They improve over classical Control Barrier Functions (CBFs), which are usually overly conservative. Our dCBF solution relaxes the CBF definitions by (i) using environmental dependencies and (ii) embedding them into differentiable quadratic programs. These novel safety layers are called BarrierNet. They can be used in conjunction with any neural network-based controller. They are trained by gradient descent. With BarrierNet, the safety constraints of a neural controller become adaptable to changing environments. We evaluate BarrierNet on several problems: robot traffic merging, robot navigation in 2D and 3D spaces, end-to-end vision-based autonomous driving in a sim-to-real environment and in physical experiments, and demonstrate their effectiveness compared to state-of-the-art approaches.

Tsun-Hsuan Wang
Massachusetts Institute of Technology
tsunw@mit.edu

MS41

Network Boundary Control of the Semilinear Isothermal Euler Equation Modeling Gas Transport on a Network of Pipelines

In this talk, we briefly discuss the analysis and tracking type optimal control of the nonlinear transport of gas in a network of pipelines. The gas distribution's evolution on a given pipe is modeled by an isothermal semilinear compressible Euler system in one space dimension. On the network, solutions satisfying (at nodes) the so-called Kirchoff flux continuity conditions are shown to exist within the vicinity of an equilibrium state. The nonlinear optimization problem then aims at driving such dynamics to a given target distribution by the means of suitable (network) boundary controls while keeping the distribution within given (state) constraints.

Marcelo Bongarti
Weierstrass Institute for Applied Analysis and Stochastics
Berlin, Germany
bongarti@wias-berlin.de

Michael Hintermueller
Weierstrass Institute for Applied Analysis and Stochastics
hintermueller@wias-berlin.de

MS41

Stability for Degenerate Evolution Equations

We consider an evolution problem on $(0, 1)$ with degeneracy at $x = 0$. We assume Dirichlet condition at $x = 0$, while at $x = 1$ we impose a suitable damping boundary condition. Clearly the presence of a degenerate function leads us to use different spaces with respect to the standard ones and it gives rise to some new difficulties. However, thanks to some suitable assumptions on the function, one can prove some estimates on the associated energy that are crucial to drive the solution to 0 at some time T or to obtain a uniform exponential decay.

Genni Fragnelli
Universita degli Studi di Bari
genni.fragnelli@unitus.it

MS41

Results on Classical Elastohydrodynamics for a

Swimming Filament

We consider two models of an immersed inextensible filament undergoing planar motion in 3D: (1) the classical elastohydrodynamic model using resistive force theory coupled with Euler-Bernoulli beam theory, and (2) a novel curve evolution formulation incorporating the effects of linear viscoelasticity. We mention our recent PDE results on these models and highlight how this analysis can help to better understand and optimize undulatory swimming at low Reynolds number. This includes the development of a novel numerical method to simulate inextensible swimmers in Newtonian and viscoelastic media.

Laurel Ohm
Princeton University
laurel.ohm@princeton.edu

MS41

Optimal Control in Poroelastic Systems

We consider an optimal control problem subject to an elliptic-parabolic coupled system of partial differential equations that describes fluid flow through biological tissues. Our goal is to optimize the fluid pressure and solid displacement using distributed or boundary control. We first show results on the existence and uniqueness of optimal controls and then present necessary optimality conditions. The optimal controls can be approximated numerically.

Sarah L. Strikwerda
North Carolina State University
slstrikw@ncsu.edu

MS42

Controllability Spaces for some PDEs with Internal Point Masses

I will describe some models for internal point masses within a variety systems such as elastic systems, Schrodinger equations and the heat equation. Of particular interest is a description of the controllability spaces with a control active at an endpoint. In the case of a Schrodinger system the controllability spaces depend upon the position of the point mass. In some cases, the point mass "smooths" the control space by one Sobolev order, and in other cases there is no such smoothing. This also applies to an Euler-Bernoulli beam with a point mass. Some particular examples will be discussed in detail.

Scott Hansen
Iowa State University
Department of Mathematics
shansen@iastate.edu

MS42

Domain Decomposition for a Coupled FEM/ROM Model of the Stokes-Elasticity System

We present a partitioned method for FSI problems based on a monolithic formulation of the problem, which employs a Schur complement equation for a Lagrange multiplier. This algorithm eradicates the need for iterations between the fluid and structure subdomains and instead allows them to be decoupled and solved separately at each time step. The Lagrange multiplier, representing an approximation of the interface flux, serves as a Neumann boundary condition for each sub-problem, allowing for the fluid and structure to be solved independently at each time step. To reduce computational costs, we consider implementing a reduced order model (ROM) for one or both subdomains. The Schur complement method developed for the original FSI scheme can be utilized to couple a reduced order model with either a full order model or a reduced order model on the other subdomain. We show numerical results demonstrating the methods capability to capture each type of coupling.

Hyesuk Lee
Clemson University
School of Mathematical and Statistical Sciences
hklee@clemson.edu

MS42

Stabilizing Phenomenon for Electrically Conducting Fluids

Physical experiments have observed that the magnetic field can stabilize and damp electrically conducting fluids. This talk presents rigorous stability and decay results that appear to reveal the mechanism behind this remarkable stabilizing phenomenon. We consider the perturbations near a background magnetic field governed by the 3D incompressible magneto-hydrodynamic (MHD) equations with dissipation in only one direction. Without the magnetic field, the fluid is not known to be stable. But we show that the magnetic field in this MHD system stabilizes and damps the fluid. In fact, we obtain precise large-time decay behavior of the fluid. Mathematically the MHD system can be converted into wave equations, which reveal the enhanced smoothing and stabilizing effects.

Jiahong Wu
Oklahoma State University
jiahong.wu@okstate.edu

MS42

Numerical Approximations for Time Dependent FSI PDE Systems

In this paper, we introduce numerical approximations to a coupled incompressible fluid-structure PDE system. We propose a numerical scheme to solve this time dependent coupled PDE system and show the convergence analysis to the related numerical scheme. Finally, we provide numerical examples to justify our theoretical results.

Ahmed Zytoon
Iowa State University
zytoon@iastate.edu

MS43

First Order Conditions for Optimality for Non-Smooth Risk-Averse Optimal Control

We derive first-order necessary conditions for optimality, in the form of a Pontryagin Maximum Principle, for risk-averse stochastic optimal control problems subject to final time inequality constraints, and whose costs are general, possibly non-smooth finite coherent risk measures. Unlike preexisting contributions covering this situation, our analysis holds for dynamics which stem from stochastic differential equations driven by standard Wiener processes. In addition, thanks to a thorough use of stochastic set-valued analysis and differential inclusions, it presents the advantages of neither involving second-order adjoint equations, nor leading to the so-called weak version of the Pontryagin Maximum Principle, in which the maximization condition with respect to the control variable is replaced by the stationarity of the Hamiltonian.

Riccardo Bonalli
CNRS, France
riccardo.bonalli@centralesupelec.fr

MS43

Brownian Motion and Grushin-Type Singularities

The Grushin plane is a paradigmatic example of an optimal control problem with linear control and quadratic cost. Moreover, the optimal paths can be naturally understood in terms of the geodesics in almost-Riemannian geometry. While the geodesics can cross the singularity, the heat flow, equivalently Brownian motion, cannot, which shows that the ability to cross the singularity does not survive the addition of white noise. We consider a one-parameter family of Grushin-type singularities, explain the crossing or non-crossing of the singularity in terms of the classical theory of Bessel processes and boundary conditions for one-dimensional diffusions, and indicate best extensions of Brownian motion to the singularity in the cases where crossing is possible.

Robert Neel
Department of Mathematics
Lehigh University
robert.neel@lehigh.edu

MS43

Reproducing Sensory Induced Visual Hallucinations via Neural Fields, a Case for the Non-Linearity

Understanding the interaction between retinal stimulation and the cortical response in the primary visual cortex (V1 for short) is a significant challenge in improving our insight into human perception and visual organisation. In this talk we will we focus on pattern formation in the visual cortex when the cortical activity is driven by a geometric visual hallucination-like stimulus. We will present recent work, in collaboration with Y. Chitour and C. Tamekue, on the reproduction of various visual illusions via a control theoretical approach to continuous neural field models (Wilson-Cowan equations), with a particular focus on MacKay-type effects (i.e., phantom images induced by geometric patterns). Our main result consists in showing that while the classical MacKay effect (Nature, 1957) can be recovered via a linear model, the experiences of Billock and Tsou (PNAS, 2007) are fundamentally due to the presence non-linear nature of the neuronal response function. These results are novel both for the employed techniques, which do not rely on the cortical activity to be near a bifurcation, and since they show that the standard bifurcation analysis approach, based on the study of the linearised system, cannot recover the Billock and Tsou phenomena.

Dario Prandi
Université Paris Saclay, France
dario.prandi@centralesupelec.fr

MS43

Topological and Structural Features of Quantum Control Landscapes

Optimization of a quantum objective naturally can be expressed in terms of a landscape, which is the objective value being optimized as a functional of the control field. Typical objectives include maximizing an observable or creating a particular unitary transformation. The landscape topological features (critical points) and the structural features (the 'twists and turns' encountered when climbing the landscape) are important to understand in order to assess the ease of performing quantum objective optimization. In the case of closed finite dimensional quantum systems, results will be presented on the topological features of the landscapes. Attention will also be given to the structural features of control landscapes, where simulations and some experiments show that the gradient algorithm permits finding near straight shots through control space from the initial to the optimal field. Finally, some recent results will be presented as evidence for the connectedness of the landscape top manifold. The top manifold can be viewed as a control resource for optimizing ancillary criteria besides the main objective value. The collective findings bode well for quantum control, but much remains to be explored.

Herschel Rabitz
Department of Chemistry
Princeton University
hrabitz@Princeton.EDU