39th Southern California Control Workshop

Technical Program

8:00-8:50	Light breakfast (coffee, bagels and fruits)
8:50-9:00	Welcome remarks by **Magnus Egerstedt**, Stacey Nicholas Dean of Engineering, UCI Samueli School of Engineering
Session I	Chair: David Copp
9:00-9:20	*Provably Correct Training of Neural Network Controllers Using Reachability Analysis* **Xiaowu Sun** (UCI), Advisor: Yasser Shoukry
9:20-9:40	*Refining Control Barrier Functions using Hamilton-Jacobi Reachability* **Sander Tonkens** (UCSD), Advisor: Sylvia Herbert
9:40-10:00	*Preference-Based Learning and Control: Realizing Dynamic Locomotion on Bipedal Robots and Exoskeletons* **Maegan Tucker** (Caltech), Advisor: Aaron Ames
10:00-10:20	*PASTA: Provably Accurate Simple Transformation Alignment* **Matteo Marchi** (UCLA), Advisor: Paulo Tabuada
10:20-10:50	Break
Session II	Chair: Jorge Cortés
10:50-11:10	*Safety-Critical Control as a Design Paradigm for Solvers of Constrained Nonlinear Programs* **Ahmed Allibhoy** (UCSD), Advisor: Jorge Cortes
11:10-11:30	*A Martingale Approach to the Predictability of Patterns in Discrete-Event Stochastic Systems* **SooJean Han** (Caltech), Advisors: John Doyle, Soon-Jo Chung
11:30-11:50	*Energy harvesting from anisotropic fluctuations* **Olga Movilla Miangolarra** (UCI), Advisor: Tryphon Georgiou
11:50-12:10	*Online stabilization of unknown networked systems with communication constraints* **Jing Yu** (Caltech), Advisors: Adam Wierman, John Doyle

12:10-13:30	Lunch (boxed lunches, lemonade,..)
Session III	Chair: Andrew Teel
13:30-13:50	*Macroscopic network circulation for planar graphs* **Fariba Ariaei** (UCI), Advisor: Tryphon Georgiou
13:50-14:10	*On Generalizing the Perron-Frobenius Theorem to Time-Varying Networks* **Rohit Parasnis** (UCSD), Advisors: Behrouz Touri, Massimo Franceshetti
14:10-14:30	*Preserving Lagrangian structure in data-driven reduced-order modeling of large-scale mechanical systems* **Harsh Sharma** (UCSD), Advisor: Boris Kramer
14:30-14:50	*ACD-EDMD: Analytical Construction for Dictionaries of Lifting Functions in Koopman Operator-based Nonlinear Robotic Systems* **Lu Shi** (UCR), Advisor: Konstantinos Karydis
14:50-15:20	Break (coffee and snacks)
Session IV	Chair: Solmaz Kia
15:20-15:40	*Distributed Invariant Extended Kalman Filter (DIEKF) for 3-D Dynamic State Estimation* **Jie Xu** (UCR), Advisor: Wei Ren
15:40-16:00	*Avoiding Unintended Consequences: How Incentives Aid Information Provisioning in Bayesian Congestion Games* **Bryce Ferguson** (UCSB), Advisor: Jason Marden
16:00-16:20	*Robustness and Consistency in Linear Quadratic Control with Untrusted Predictions* **Tongxin Li** (Caltech), Advisors: Steven Low, Adam Wierman
16:20	Adjournment

Abstracts

Session I

Provably Correct Training of Neural Network Controllers Using Reachability Analysis
Xiaowu Sun (UCI), Advisor: Yasser Shoukry
Abstract: Neural networks (NNs) are attractive for the realization of feedback controllers; however, their adoption is significantly hindered by concerns about their safety and reliability. In this talk, I will present a new approach to train NN controllers for uncertain nonlinear dynamical systems to fulfill unseen tasks. The proposed approach combines model-based design methodologies with data-driven learning techniques to achieve this target. I will discuss how to use the knowledge of dynamical model to guide and bias the neural network training, and provide strong correctness guarantees even when deploying the NN-controlled autonomous system in environments that were not present in the training data.

Refining Control Barrier Functions using Hamilton-Jacobi Reachability
Sander Tonkens (UCSD), Advisor: Sylvia Herbert
Abstract: Safety filters based on Control Barrier Functions (CBFs) have emerged as a practical tool for the safety-critical control of autonomous systems. These approaches encode safety through a value function and enforce safety by imposing a constraint on the time derivative of this value function. However, synthesizing a valid CBF that is not overly conservative in the presence of input constraints is a notorious challenge. In this work, we propose refining candidate CBFs using formal verification methods to obtain a valid CBF. In particular, we update an expert-synthesized or backup CBF using dynamic programming (DP) based reachability analysis. Our framework guarantees that with every DP iteration the obtained CBF is provably at least as safe as the prior iteration and converges to a valid CBF. Therefore, our proposed method can be used in-the-loop for robotic systems. We demonstrate the practicality of our method to enhance safety and/or reduce conservativeness on a range of nonlinear control-affine systems in simulation using various CBF synthesis techniques.

Preference-Based Learning and Control: Realizing Dynamic Locomotion on Bipedal Robots and Exoskeletons
Maegan Tucker (Caltech), Advisor: Aaron Ames
Abstract: Achieving locomotive stability is challenging enough from a robotics and control perspective, let alone addressing the added complexity of satisfying subjective gait preferences of a human operator. Moreover, traditional approaches to locomotion typically require extensive manual parameter tuning. Thus, the goal of this talk is to discuss how theoretic approaches to bipedal locomotion, based upon nonlinear controllers with formal guarantees of stability, can be coupled with learning to achieve stable locomotion without the need for manual parameter tuning. Ultimately, this work provides a framework for achieving locomotion by formally combining techniques from learning and control. The result of this framework is experimentally demonstrated across several platforms including the bipedal robot Cassie and a full lower-body exoskeleton.

PASTA: Provably Accurate Simple Transformation Alignment

Matteo Marchi (UCLA), Advisor: Paulo Tabuada

Abstract: LiDAR is a widely used sensor for self-localization and SLAM algorithms. Most of these algorithms rely on solving the point cloud registration problem as a subroutine. While many registration methods exist, most are local, i.e., they only converge when presented with similar point clouds. Moreover, they offer no formal guarantees on their performance. In this work we present a low-complexity global point registration technique that is suitable for point clouds generated from LiDAR scans and has formal worst-case error guarantees under mild convexity assumptions on the environment. Moreover, we empirically show that the proposed method compares favorably, on real LiDAR data, to state of the art methods such as ICP.

Session II

Safety-Critical Control as a Design Paradigm for Solvers of Constrained Nonlinear Programs

Ahmed Allibhoy (UCSD), Advisor: Jorge Cortes

Abstract: The problem of designing a feedback controller to ensure that the state of a nonlinear system satisfies constraints, referred to as safety-critical control, has gotten considerable attention in recent years due to the enormous number of applications in areas such as robotics and automotive systems. However, methods used to design safeguarding controllers also have an important role to play in optimization theory. In this talk, we show that many problems in convex optimization can be interpreted as safety critical control problems. By blending techniques from safety-critical control with tools from monotone operator theory, we design algorithms to solve these problems. In some cases our approach leads to reinterpretations of well-known algorithms from the lens of control theory, and in other cases we derive entirely novel algorithms. Our results demonstrate the promising potential of safety-critical control for both the analysis and design of optimization algorithms.

A Martingale Approach to the Predictability of Patterns in Discrete-Event Stochastic Systems

SooJean Han (Caltech), Advisor: John Doyle and Soon-Jo Chung

Abstract: In this talk, we consider discrete-event stochastic systems whose event process is finite-valued but generated from unknown statistics. We construct a hidden Markov model representation of the event process and focus on analyzing recurrent patterns. We use martingale theory to derive closed-form expressions for quantities related to the prediction of patterns, such as the mean duration between consecutive occurrences of patterns and their first occurrence probabilities. We demonstrate an application to the control of large-scale networks.

Energy harvesting from anisotropic fluctuations

Olga Movilla Miangolarra (UCI), Advisor: Tryphon Georgiou

Abstract: We consider a rudimentary model for a heat engine, known as the Brownian gyrator, that consists of an overdamped system with two degrees of freedom in an anisotropic temperature field. Whereas the hallmark of the gyrator is a nonequilibrium steady-state curl-carrying probability current that can generate torque, we explore the coupling of this natural gyrating motion with a periodic actuation potential for the purpose of extracting work. We show that path-lengths traversed in the manifold of thermodynamic states, measured in a suitable Riemannian metric, represent dissipative losses, while area integrals of a work-density quantify work being extracted. Thus, the stochastic control problem of maximizing work output relates to an isoperimetric problem, trading off area against length of an encircling path. We derive an isoperimetric inequality that provides a universal bound on the efficiency of all cyclic operating protocols, and a bound on how fast a closed path can be traversed before it becomes impossible to extract positive work. The analysis presented provides guiding principles for building autonomous engines that extract work from anistropic fluctuations.

Online stabilization of unknown networked systems with communication constraints

Jing Yu (Caltech), Advisor: Adam Wierman and John Doyle

Abstract: We investigate the problem of stabilizing an unknown networked linear system under communication constraints and adversarial disturbances. We propose the first provably stabilizing algorithm for the problem. The algorithm uses a distributed version of nested convex body chasing to maintain a consistent estimate of the network dynamics and applies system level synthesis(SLS) to determine a distributed controller based on this estimated model. Our approach avoids the need for system identification and accommodates a broad class of communication delay while being fully distributed and scaling favorably with the number of subsystems in the network.

Session III

Macroscopic network circulation for planar graphs

Fariba Ariaei (UCI), Advisor: Tryphon Georgiou

Abstract: The analysis of networks, aimed at suitably defined functionality, often focuses on partitions into subnetworks that capture desired features. Chief among the relevant concepts is a 2-partition; this underlies the classical Cheeger inequality and highlights a “constriction” (bottleneck) that limits accessibility between the respective parts of the network. In a similar spirit, we explored a notion of global circulation which necessitates a concept of a 3-partition that exposes this macroscopic feature of network flows. Graph circulation is often present in transportation networks as well as in certain biological networks. In this talk, I will introduce a notion of circulation for general graphs and then focus on planar graphs. For the case of the latter I will explain that a scalar potential characterizes circulation in complete analogy with the curl of planar vector fields and present an algorithm for determining values of the potential and, hence, quantify circulation. I then will discuss alternative notions of circulation, explain how these may depend on graph embedding, draw parallels between networks and Helmholtz-Hodge decomposition of vector fields, and conclude with a suggestive application of the framework in detecting abnormalities in cardiac circulatory physiology.

On Generalizing the Perron-Frobenius Theorem to Time-Varying Networks

Rohit Parasnis (UCSD), Advisor: Behrouz Touri and Massimo Franceshetti

Abstract: Perron-Frobenius theorem is a fundamental tool in matrix analysis that has applications to probability theory, complex networks, population dynamics, social learning,

internet search engines, and in the studies of numerous engineering, physical, and economic phenomena. However, this theorem and many of its extensions can be applied only to a single matrix at a time, thereby limiting their applications in understanding networked dynamical systems to static networks. To extend the applicability of these results to time-varying networks, we generalize two assertions of the Perron-Frobenius theorem to sequences as well as continua of row-stochastic matrices. Besides having important implications for both discrete-time and continuous-time distributed averaging and for non-Bayesian learning, our results have potential applications in related areas such as distributed optimization and estimation, and more generally, in advancing the state-of-the-art understanding of dynamical processes over real-world networks.

Preserving Lagrangian structure in data-driven reduced-order modeling of large-scale mechanical systems

Harsh Sharma (UCSD), Advisor: Boris Kramer

Abstract: We present a nonintrusive physics-preserving method to learn reduced-order models (ROMs) of Lagrangian mechanical systems. Existing intrusive projection-based model reduction approaches construct structure-preserving Lagrangian ROMs by projecting the Euler-Lagrange equations of the full-order model (FOM) onto a linear subspace. This Galerkin projection step requires complete knowledge about the Lagrangian operators in the FOM and full access to manipulate the computer code. In contrast, the proposed Lagrangian operator inference approach embeds the mechanics into the operator inference framework to develop a data-driven model reduction method that preserves the underlying Lagrangian structure. The method does not require access to FOM operators or computer code. The numerical results demonstrate Lagrangian operator inference on an Euler-Bernoulli beam model and a large-scale discretization of a soft robot fishtail with 779,232 degrees of freedom. For the high-dimensional soft-robotic fishtail model, the learned Lagrangian ROMs track the change in system energy accurately in the presence of dissipation and time-dependent control input and work well even for unknown control inputs. Moreover, our method achieves significant reduction in state dimension, which makes the learned ROMs ideal for real-time control and state estimation.

ACD-EDMD: Analytical Construction for Dictionaries of Lifting Functions in Koopman Operator-based Nonlinear Robotic Systems

Lu Shi (UCR), Advisor: Konstantinos Karydis

Abstract: Koopman operator theory has been gaining momentum for model extraction, planning, and control of data-driven robotic systems. The Koopman operator's ability to extract dynamics from data depends heavily on the selection of an appropriate dictionary of lifting functions. In this paper we propose ACD-EDMD, a new method for Analytical Construction of Dictionaries of appropriate lifting functions for a range of data-driven Koopman operator based nonlinear robotic systems. The key insight of this work is that information about fundamental topological spaces of the nonlinear system (such as its configuration space and workspace) can be exploited to steer the construction of Hermite polynomial-based lifting functions. We show that the proposed method leads to dictionaries that are simple to implement while enjoying provable completeness and convergence guarantees when observables are weighted bounded. We evaluate ACD-EDMD using a range of diverse nonlinear robotic systems in both simulated and physical hardware experimentation (a wheeled mobile robot, a two-revolute-joint robotic arm, and a soft robotic leg). Results reveal that our method leads to dictionaries that enable high-accuracy prediction and that can generalize to diverse validation sets. The associated GitHub repository of our algorithm can be accessed at https://github.com/UCR-Robotics/ACD-EDMD.

Distributed Invariant Extended Kalman Filter (DIEKF) for 3-D Dynamic State Estimation
Jie Xu (UCR), Advisor: Wei Ren
Abstract: Distributed Kalman filters have been widely studied in vector space and been applied to 2-D target state estimation using sensor networks. We present a novel DIEKF algorithm that exploits matrix Lie groups and is suitable to track the target's 6-DOF motion in a 3-D environment. The DIEKF algorithm is based on the proposed extended Covariance Intersection (CI) algorithm that guarantees consistency in matrix Lie groups. We show that the proposed algorithm is more accurate and more consistent than the quaternion-based extended Kalman filter by simulations in a camera network to track a target in a fully distributed manner.

Session IV

Avoiding Unintended Consequences: How Incentives Aid Information Provisioning in Bayesian Congestion Games
Bryce Ferguson (UCSB), Advisor: Jason Marden
Abstract: When users lack specific knowledge of various system parameters, their uncertainty may lead them to make undesirable deviations in their decision making. To alleviate this, an informed system operator may elect to signal information to uninformed users with the hope of persuading them to take more preferable actions. In this work, we study public
and truthful signalling mechanisms in the context of Bayesian congestion games on parallel networks. We provide bounds on he possible benefit a signalling policy can provide with and without the concurrent use of monetary incentives. We find that though revealing information can reduce system cost in some settings, it can also be detrimental and cause worse performance than not signalling at all. However, by utilizing both signalling and incentive mechanisms, the system operator can guarantee that revealing information does not worsen performance while offering similar opportunities for improvement. These findings emerge from the closed form bounds we derive on the benefit a signalling policy can provide. We provide a numerical example which illustrates the phenomenon that revealing more information can degrade performance when incentives are not used and improves performance when incentives are used.

Robustness and Consistency in Linear Quadratic Control with Untrusted Predictions
Tongxin Li (Caltech), Advisor: Steven Low and Adam Wierman
Abstract: We study the problem of learning-augmented predictive linear quadratic control. Our goal is to design a controller that balances "consistency", which measures the competitive ratio when predictions are accurate, and "robustness", which bounds the competitive ratio when predictions are inaccurate. We propose a novel λ-confident controller and prove that it maintains a competitive ratio upper bound of $1+\min\{O(\lambda^2\varepsilon)+

O(1-\lambda)^2,O(1)+O(\lambda^2)\}$ where $\lambda\in [0,1]$ is a trust parameter set based on the confidence in the predictions, and ε is the prediction error. Further, motivated by online learning methods, we design a self-tuning policy that adaptively learns the trust parameter λ with a competitive ratio that depends on ε and the variation of system perturbations and predictions. We show that its competitive ratio is bounded from above by $ 1+{O(\varepsilon)}/({{\Theta(1)+\Theta(\varepsilon)}})+O(\mu_{\mathsf{Var}})$ where μ_Var measures the variation of perturbations and predictions. It implies that by automatically adjusting the trust parameter online, the self-tuning scheme ensures a competitive ratio that does not scale up with the prediction error ε.

Title

Alexander Davydov (UCSB), Advisor: Francesco Bullo

Abstract: