## Session I

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### Session II

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<td>Opportunistic integrity monitoring for enhanced safety of autonomous vehicles</td>
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Session I

Title: Data-driven control with performance guarantees: variable speed limit design for highways

Presenter: Dan Li (UC San Diego), Advisor: Sonia Martinez

Abstract: This talk studies the data-driven design of variable speed limits for highways subject to uncertainty, including unknown driver actions as well as vehicle arrivals and departures. With accessibility to sample measurements of the uncertain variables, we aim to find the set of speed limits that prevents traffic congestion and an optimum vehicle throughput with high probability. This results into the formulation of a stochastic optimization problem (P), which is intractable due to the unknown distribution of the uncertainty variables. By developing a distributionally robust optimization framework, we present an equivalent and yet tractable reformulation of (P). Further, we propose an efficient algorithm that provides suboptimal data-driven solutions and guarantees congestion-free conditions with high probability. We employ the resulting control method on a traffic simulator to illustrate the effectiveness of this approach.

Title: Accuracy prevents robustness in data-driven algorithms

Presenter: Abed AlRahman Al Makdah (UC Riverside), Advisor: Fabio Pasqualetti

Abstract: In this work, we take an important step towards proving the existence of a fundamental trade-off between accuracy and robustness for data-driven algorithms. In particular, we formally show that, in a quest to optimize their accuracy, data-driven algorithms - including those based on machine learning techniques - inevitably become more sensitive to (accidental or malicious) data variations. We study this tradeoff in a binary classification problem, as well as, in a perception-based control problem, where control decisions rely solely on data-driven, and often incompletely trained, perception maps.

Title: Robust model-free learning and control without prior knowledge

Presenter: Dimitar Ho (Caltech), Advisor: John C. Doyle

Abstract: We present a simple model-free control algorithm that is able to robustly learn and stabilize an unknown discrete-time linear system with full control and state feedback subject to arbitrary bounded disturbance and noise sequences. The controller does not require any prior knowledge of the system dynamics, disturbances or noise, yet can guarantee robust stability, uniform asymptotic bounds and uniform worst-case bounds on the state-deviation. Rather than the algorithm itself, we would like to highlight the new approach taken towards robust stability analysis which served as a key enabler in providing the presented stability and performance guarantees. We will conclude with simulation results that show that despite the generality and simplicity, the controller demonstrates good closed-loop performance.

Title: Efficient identification of linear evolutions in nonlinear vector fields: Koopman invariant subspaces

Presenter: Masih Haseli (UC San Diego), Advisor: Jorge Cortes

Abstract: This talk presents a data-driven approach to identify finite-dimensional Koopman invariant subspaces and eigenfunctions of the Koopman operator. Given a dictionary of functions and a collection of data snapshots of the dynamical system, we rely on the Extended Dynamic Mode Decomposition (EDMD) method to approximate the Koopman operator. We start by establishing that, if a function in the space generated by the dictionary evolves linearly according to the dynamics, then it must correspond to an eigenvector of the matrix obtained by EDMD. A counterexample shows that this necessary condition is however not sufficient. We then propose a necessary and sufficient condition for the identification of linear evolutions according to the dynamics based on the application of EDMD forward and backward in time. Given the high computational cost of checking this condition, we propose an alternative characterization based on the identification of the largest Koopman invariant subspace in the span of the dictionary. This leads us to introduce the Symmetric Subspace Decomposition strategy to identify linear evolutions using efficient linear algebraic methods. Various simulations illustrate our results.

Title: Convergence and sample complexity of gradient methods for the model-free linear quadratic regulator problem

Presenter: Hesameddin Mohammadi (USC), Advisor: Mihailo Jovanovic
Abstract: Model-free reinforcement learning attempts to find an optimal control action for an unknown dynamical system by directly searching over the parameter space of controllers. The convergence behavior and statistical properties of these approaches are often poorly understood because of the nonconvex nature of the underlying optimization problems as well as the lack of exact gradient computation. In this talk, we take a step towards demystifying the performance and efficiency of such methods by focusing on the standard infinite-horizon linear quadratic regulator problem for continuous-time systems with unknown state-space parameters. We establish exponential stability for the ordinary differential equation (ODE) that governs the gradient-flow dynamics over the set of stabilizing feedback gains and show that a similar result holds for the gradient descent method that arises from the forward Euler discretization of the corresponding ODE. We also provide theoretical bounds on the convergence rate and sample complexity of a random search method. Our results demonstrate that the required simulation time for achieving $\epsilon$-accuracy in a model-free setup and the total number of function evaluations both scale as $\log (1/\epsilon)$. 
Session II

Title: Robust controller design for stochastic nonlinear systems via convex optimization
Presenter: Hiroyasu Tsukamoto (Caltech), Advisor: Soon-Jo Chung

Abstract:
This paper presents a new nonlinear control design framework, called ConVex optimization-based Stochastic steady-state Tracking Error Minimization (CV-STEM), for a class of Itô stochastic nonlinear systems including stochastic Lagrangian systems. This state feedback controller design involves the use of multiple State-Dependent Coefficient (SDC) models of a nonlinear system equation and computes its controller parameters by solving a convex optimization problem in order to minimize an upper bound of the steady-state tracking error. This problem is shown to be equivalent to the original nonlinear optimization problem of minimizing the upper bound. The exponential stability and robustness properties due to the state-dependent Riccati inequality are proven using stochastic contraction analysis. Discrete-time stochastic incremental contraction analysis with respect to a state- and time-dependent metric is also presented along with its explicit connection to continuous-time contraction analysis. A result of simulation is used to validate the superiority of the proposed controller compared to a known nonlinear controller, a PID controller, and an H-infinity controller.

Title: Extremum seeking without persistent control oscillation
Presenter: Mahmoud Abdelgalil (UC Irvine), Advisor: Haithem Taha

Abstract: Extremum-Seeking is an adaptive control technique known to mimic, on average, the gradient flow of a static/dynamic unknown function using only online measurements of function value [4]. Most extremum-seeking algorithms achieve a weak notion of stability of the set of minimizers known as Practical Stability [5]. In recent years [2], a connection between extremum-seeking and trajectory approximation results for systems with highly oscillatory control signals was discovered and utilized to analyze stability for some extremum-seeking frameworks. For such systems, a clever design choice of the vector fields [7, 3] could achieve asymptotic/exponential stability provided that the function to be optimized satisfies certain properties. One of the common and main assumptions is that the value of the function at the minimum point is zero or is known exactly. If that assumption is violated, asymptotic/exponential stability in the sense of lyapunov is no longer guaranteed and only practical stability results can be achieved. In this endeavor, we aim at relaxing that assumption. We show that, by introducing an additional equation, there is a frequency of oscillation for the new system, which evolves on the epigraph of the function, such that the (unique) minimum point has asymptotic/exponential stability properties with respect to a certain subset [1] of the epigraph, which depends on the chosen frequency. Although a similar framework appears in the recent work [6], the control effort required by the mentioned framework grows without bound as the system approaches the minimum point even in the absence of a drift vector field. Our proposed framework, however, achieves said stability results with bounded control input, although there are still two parameter to be tuned. Despite the fact that such stability results hold only for a subset of possible initial conditions, this framework still has merit since it is always possible to initialize the system in such set because it only requires online measurements of function value, the readiness of which is assumed as the underlying feature of extremum seeking, including at the initial point.

Title: A simple hierarchy for computing controlled invariant sets
Presenter: Janis Anevlavis (UC Los Angeles), Advisor: Paulo Tabuada

Abstract: In this talk we revisit the problem of computing controlled invariant sets for controllable discrete-time linear systems and present a novel hierarchy for their computation. The key insight is to lift the problem to a higher dimensional space where the maximal controlled invariant set can be computed exactly and in closed-form for the lifted system. By projecting this set into the original space we obtain a controlled invariant set that is a subset of the maximal controlled invariant set for the original system. Building upon this insight we describe in this paper a hierarchy of spaces where the original problem can be lifted into so as to obtain a sequence of increasing controlled invariant sets. The algorithm that results from the proposed hierarchy does not rely on iterative computations. We illustrate the performance of the proposed method on a variety of scenarios exemplifying its appeal.

Title: On the gap between system level synthesis and structured controller design: the case of relative feedback
Presenter: Emily Jensen (UC Santa Barbara), Advisor: Bassam Bamieh

Abstract: We consider the optimal distributed controller design problem with subcontroller communication constraints, by designing controllers whose state space realizations are composed of matrices with a specified sparsity pattern. Optimiz-
ing over the set of controllers with such structured realizations remains an unsolved problem, but the recently developed System Level Synthesis (SLS) framework provides a computationally tractable method for optimizing over a convex subset of these structured realizable controllers, which we refer to as closed-loop structured controllers. The performance of the optimal closed-loop structured controller will in general provide a bound on the performance of the optimal controller with structured realization. We are interested in quantifying this bound, and take a first step toward solving this problem by considering the setting of relative feedback controllers. Our main result demonstrates through an example that, when relative feedback constraints are imposed, this gap in performance may be infinite.
Session III

Title: Smarts or strength? Asymmetric information in Blotto games
Presenter: Keith Paarporn (UC Santa Barbara), Advisors: Jason Marden and Mahnoosh Alizadeh
Abstract: We investigate informational asymmetries in the Colonel Blotto game, a game-theoretic model of competitive resource allocation between two players over a set of battlefields. One of the two players knows the battlefield valuations with certainty, whereas the other knows only a distribution on the values. In this zero-sum Bayesian setting, we solve for the unique equilibrium payoffs and quantify a value of information - how much is information worth in terms of actual resource assets? Though information can never give a weaker player the competitive advantage when there are only two battlefields, we show information can compensate for a lack of resources in three or more battlefields.

Title: Information design for non-atomic routing games: revelation principle and long run behavior
Presenter: Yixian Zhu (USC), Advisor: Ketan Savla
Abstract:
We consider a routing game among non-atomic agents where link latency functions are conditional on an unknown state of the network. All the agents have the same prior belief about the state, but only a fixed fraction privately accesses additional noisy information conditional on the state and forms corresponding posterior beliefs following Bayesian update. The outcome of the single stage game is Bayesian Nash flow induced by the beliefs. The signal which maps the state to information is to be designed to minimize a social cost associated with the induced flow. A refinement of the revelation principle is shown to hold according to which, among all public and private signals with realizations in a finite set, it is sufficient to restrict to the set of obedient private direct signals, i.e., which privately recommend routes that are optimal with respect to posteriors. We then consider an infinitely repeated stage setting under a fixed direct private signal, where the fraction of agents who obey private recommendations in each stage is proportional to a publicly known rating at that stage. This rating is related to the time average of the stage-wise cumulative, over all agents, difference in observed latencies between recommended and alternate routes. If the fixed private signal is obedient, and the distribution of alternate route for each agent is fixed, then we show that the multi-stage outcome, i.e., link flows, in almost sure sense converges to the outcome of the single stage game when all agents following recommendations of the same private signal.

Title: Adaptive learning in two-player Stackelberg games with continuous action sets
Presenter: Guosong Yang (UC Santa Barbara), Advisor: Joao Hespanha
Abstract: We study a two-player Stackelberg game in which the follower’s strategy depends on a parameter vector that is unknown to the leader. An adaptive learning algorithm is designed to simultaneously estimate the unknown parameter and minimize the leader’s cost, based on adaptive control techniques and hysteresis switching. The algorithm guarantees that the leader’s cost predicted using the parameter estimate becomes indistinguishable from its actual cost in finite time, up to a preselected, arbitrarily small error threshold, and that the first-order necessary condition for optimality holds asymptotically for the predicted cost. If an additional persistent excitation condition holds, then the parameter estimation error can also be bounded by a preselected, arbitrarily small threshold in finite time. The algorithm and convergence results are illustrated via a simple simulation example in the domain of network security.

Title: Dynamic locomotion and control of a Cassie bipedal robot
Presenter: Jenna Reher (Caltech), Advisor: Aaron D. Ames
Abstract:
The interplay between hardware, control, and motion planning for underactuated bipedal robots can often be difficult to bridge. In this talk, we explore a methodology to address this for the bipedal robot Cassie, which features a compliant leg morphology. This compliance has the capability to enhance dynamic and energetically efficient locomotion, but at the cost of increased complexity and underactuation to the robotic model. Using the methods of virtual constraints and hybrid zero dynamics, we develop controllers for Cassie which respect the natural compliance of the physical system and present a viable computation method to yield stable locomotion. Direct implementation of these results on physical hardware is also performed wherein we validate the proposed methodology by applying a consistent control scheme across simulation, optimization and experiment.
**Session IV**

**Title:** Optimizing the power output of a stochastic thermodynamic engine  
**Presenter:** Rui Fu (UC Irvine), **Advisor:** Tryphon T. Georgiou

**Abstract:** Classical thermodynamics aimed to quantify the efficiency of thermodynamic engines by bounding the maximal amount of mechanical energy produced compared to the amount of heat required. While this was accomplished early on, by Carnot and Clausius, the more practical problem to quantify limits of power that can be delivered, remained elusive due to the fact that quasistatic processes require infinitely slow cycling, resulting in a vanishing power output. Recent insights, drawn from stochastic models, appear to bridge the gap between theory and practice in that they lead to physically meaningful expressions for the dissipation cost in operating a thermodynamic engine over a finite time window. Building on this framework of *stochastic thermodynamics* we derive bounds on the maximal power that can be drawn by cycling an overdamped ensemble of particles via a time-varying potential while alternating contact with heat baths of different temperature ($T_c$ cold, and $T_h$ hot). Specifically, assuming a suitable bound $M$ on the spatial gradient of the controlling potential, we show that the maximal achievable power is $\frac{M}{8} (\frac{T_h}{T_c} - 1)$. Moreover, we show that this bound can be reached to within a factor of $(\frac{T_h}{T_c} - 1)/(\frac{T_h}{T_c} + 1)$ by operating the cyclic thermodynamic process with a quadratic potential.

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**Title:** Balancing and suppression of oscillations of tension and cage in dual-cable mining elevators  
**Presenter:** Ji Wang (UC San Diego), **Advisor:** Miroslav Krstic

**Abstract:** Dual-cable mining elevator has advantages in the transportation of heavy load to a large depth over the single cable elevator. However challenges occur when lifting a cage via two parallel compliant cables, such as tension oscillation inconformity between two cables and the cage roll, which have a significant effect on the safety performance of mining cable elevators. Vibration dynamics of the dual-cable mining elevator are modeled by two pairs of $2 \times 2$ heterodirectional coupled hyperbolic PDEs on a time-varying domain and all four PDE bottom boundaries are coupled at one ODE. We design an output feedback boundary control law via backstepping to exponentially stabilize the dynamic system including the tension oscillation states, tension oscillation error states and the cage roll states. The control law is constructed with the estimated states from the observer formed by available boundary measurements. The exponential stability of the closed-loop system is proved via Lyapunov analysis. Effective suppression of tension oscillations, reduction of inconformity between tension oscillations in two cables, and balancing the cage roll under the proposed controller are verified via numerical simulation.

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**Title:** A cyber-secure control-detector architecture for nonlinear processes  
**Presenter:** Scarlett Chen (UC Los Angeles), **Advisor:** Panagiotis D. Christofides

**Abstract:** This work presents a detector-integrated two-tier control architecture capable of identifying the presence of various types of cyber-attacks, and ensuring closed-loop system stability upon detection of the cyber-attacks. Working with a general class of nonlinear systems, an upper-tier Lyapunov-based Model Predictive Controller (LMPC), using networked sensor measurements to improve closed-loop performance, is coupled with lower-tier cyber-secure explicit feedback controllers to drive a nonlinear multivariable process to its steady-state. Although the networked sensor measurements may be vulnerable to cyber-attacks, the two-tier control architecture ensures that the process will stay immune to destabilizing malicious cyber-attacks. Data-based attack detectors are developed using sensor measurements via machine-learning methods, namely artificial neural networks (ANN), under nominal and noisy operating conditions, and applied online to a simulated reactor-reactor-separator process. Simulation results demonstrate the effectiveness of these detection algorithms in detecting and distinguishing between multiple classes of intelligent cyber-attacks. Upon successful detection of cyber-attacks, the two-tier control architecture allows convenient reconfiguration of the control system to stabilize the process to its operating steady-state.

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**Title:** Dynamic control allocation for a class of over-actuated aircraft  
**Presenter:** Raffaele Bagi (UC Riverside), **Advisors:** Elisa Franco (UC Los Angeles) and Andrea Serrani (Ohio State)

**Abstract:** The ability to exploit in full redundant control capabilities available in aircraft is a critical feature in actuator failure scenarios. Managing input redundancy is traditionally addressed by means of Control Allocation (CA), where the aerodynamic control surfaces are typically considered only as moment-producing devices, thereby neglecting body forces. Here, we describe a fault-tolerant control architecture for a fixed-wing over-actuated small UAV, where coupling between aerodynamic effectors and body forces are considered. The control architecture includes an adaptive loop for stable tracking of airspeed, flight path, and turn rate reference trajectories in nominal conditions (no actuator failures).
in the presence of model parameter uncertainty. Fault tolerance is provided by a Dynamic Control Allocation (DCA) mechanism that automatically redistributes the control commands to the effectors as well as modifies certain reference trajectories to maintain stability of the aircraft under multiple actuator failures. The particular design of the allocator makes the fault identification algorithms unnecessary, simplifying the overall structure of the CA technique. Simulation results are provided to illustrate the effectiveness of the controller.

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**Title:** Opportunistic integrity monitoring for enhanced safety of autonomous vehicles  

**Presenter:** Mahdi Maaref (UC Irvine), **Advisor:** Zak Kassas

**Abstract:** An opportunistic integrity monitoring framework for unmanned aerial vehicle (UAV) and autonomous ground vehicle (AGV) navigation is developed. This framework aims at fusing ambient terrestrial signals of opportunity (SOPs) with global navigation satellite system (GNSS) signals to provide tight protection level (PL) bounds. A receiver is assumed to make pseudorange measurements on multiple GNSS satellites and terrestrial SOPs. The PLs of the proposed framework are analyzed, and the reduction in the PLs of an SOP-GNSS solution over that of a GNSS-only solution is studied. It is demonstrated that adding SOP measurements, which inherently come from low elevation angles, is more effective in reducing the PLs than adding measurements from new satellites. Experimental results are presented demonstrating the performance of the proposed system.