Hierarchical Population Control: from Mean-Field Games to Social Welfare Optimization
Wei Zhang, Ohio State University

Many complex Cyber-Physical Systems (CPS) involve interactions among a large number of agents with decoupled dynamics but loosely coupled decisions due to their shared environment and resources. Such systems are often operated using a hierarchical control architecture, where a coordinator determines some macroscopic control signal to steer the population to achieve some desired group objective while respecting local preferences and constraints for individual agents. The design of hierarchical population control depends crucially on the information available to the coordinator, the rationality assumption of the agents, the individual agent dynamics and constraints, and the complex population dynamic behaviors induced by the hierarchical control strategy. This talk will introduce and discuss two emerging classes of hierarchical population control (HPC) problems, one for non-strategic agents and one for strategic agents. For non-strategic agents, the HPC problem becomes a PDE constrained optimization problem, for which some preliminary results will be briefly discussed. For strategic agents, the HPC problems are formulated as reverse Stackelberg problems, for which mean-field game becomes an important tool to characterize population behaviors. Along this direction, I will present our very recent result that establishes equivalence between an important class of mean-field control problems and the classical social welfare optimization problems in functional space.

Mean-field Games: Incentive and Reputation Mechanisms
Vijay Subramanian, University of Michigan

Motivated by systems with a large number of strategic players, such as in Internet marketplaces, we explore the use of incentive and reputation mechanisms in mean-field games.

First, we consider real-time streaming of video to co-located wireless devices where cooperation among the devices would lead to greater system efficiency. Based on ideas drawn from truth-telling auctions, we design a mechanism that achieves this cooperation via appropriate transfers (monetary payments or rebates) in a setting with a large number of devices, and with peer arrivals and departures. Furthermore, the complexity of calculating the best responses under this regime is low. We implement the proposed system on an Android testbed, and illustrate its efficient performance using real world experiments.

Next, with crowd-sourcing as the underlying motivation, we explore the impact of perceived and real reputations of agent behaviors in Internet marketplaces. We model such an Internet marketplace using a set of servers that choose prices for performing jobs. Each server has a queue of unfinished jobs, and is penalized for delay by the market-maker via a holding cost. A server completes jobs with a low or high quality, the likelihood of which is private information of the server, and jobs truthfully report the “quality” with which they were completed. The best estimate of quality based on these reports is the perceived reputation of the server. A server bases its pricing decision on the distribution of its competitors offered prices and reputations. An entering job is given a random sample of servers, and chooses the best one based on a linear combination of price and reputation. We seek to understand how prices would be determined in such a marketplace when there are a large number of users.

This is joint work with Jian Li, Rajarshi Bhattacharyya, Suman Paul, Vamseedhar Reddyvari Raja, Srinivas Shakkottai at Texas A&M University and Vinod Ramaswamy at the University of Colorado, Boulder.
On the Role of a Market Maker in Networked Cournot Competition
Subhonmesh Bose, University of Illinois at Urbana-Champaign

We study a Cournot competition among firms in a centrally managed networked marketplace. The central manager or the market maker facilitates trade between geographically separate markets via a constrained transport network. The case of wholesale electricity markets serves as our motivating example. Our focus is on understanding the consequences of different market maker designs, i.e., how the market maker’s objective in clearing the marketplace impacts the Nash equilibrium outcomes of the game between the firms and the market maker. Our results highlight that the Nash equilibrium structure is impacted dramatically by the market maker’s objective – depending on the objective, there may be a unique equilibrium, multiple equilibria, or no equilibria. Further, the game may be a potential game (as in the case of a classical Cournot competition) or not. Beyond characterizing the equilibria of the game, we provide an approach for an (approximately) optimal market maker design, when the market maker wishes to optimize a certain design objective (e.g., social welfare) at an equilibrium of the game. We also provide a sum of squares based relaxation framework to judge the approximation quality of our design choice. Additionally, our results are used to explore the value of transport (trade) and the efficiency of the market maker (as compared to a single, aggregate market).

Joint work with Desmond Cai and Adam Wierman (California Inst. of Technology).

Nash Equilibrium in Two-Stage Electricity Markets
Abhishek Gupta, Ohio State University

Generators and load serving entities bid in electricity market in multiple-stages. Although the auction scheme has been used for several decades, there is very little understanding of strategic play by big players in the market. In this talk, we will briefly review various equilibrium concepts for single-stage markets with strategic entities. We will then study Nash equilibrium in two-stage markets. Lastly, we will discuss some recent work on virtual bidding in electricity markets and its effect on market performance.

A Contract Design Approach for Phantom Demand Response
Vijay Gupta, University of Notre Dame

As the load on the power grid increases, demand side solutions become more popular. However, how to compensate customers for demand response is a still unsolved problem. Naive compensation schemes can lead to unplanned for behavior. We consider the problem of phantom demand response in which the customer is asked to reduce her consumption by a demand response aggregator (DRA) and is compensated for this reduction. However, given that the DRA must supply the customer with as much power as she desires, a strategic customer can temporarily increase her base load to report a larger reduction as a part of the demand response event. The DRA wishes to incentivize the customer both to make the maximal effort in reducing the load and to not falsify the base load. We model the problem of designing the contract by the DRA for the customer as a management contract design problem and present a solution. The optimal contract consists of two parts: a part that depends on (the possibly inflated) load reduction as measured and another that provides a share of the profit that occurs to the DRA through the demand response event to the customer.

Natural Actor-Critic Methods for Output Feedback and Decentralized Control
Andrew Lamperski, University of Minnesota

In optimal control over continuous state spaces, a challenge arises because the controller is optimized over a space of continuous functions. A common procedure to avoid this problem is to fix a parameterized form of the controller, and then optimize the parameters. The natural actor-critic method is a technique from reinforcement learning that locally optimizes the parameters by performing gradient descent with respect to the Fisher information metric generated by the parameters. Importantly, the gradient can be estimated from state and cost sequences, with no plant model. Existing natural actor-critic methods are restricted to full state-feedback problems with static controllers. In this talk, we will show how natural actor-critic methods can be extended to imperfect measurements and dynamic feedback controllers. Common problems, such as linear quadratic Gaussian control fit into this framework.
We will briefly discuss the use of natural actor-critic methods for decentralized control. In particular, we believe that it provides a promising framework to relax modeling assumptions from decentralized control, such as full plant information, as well as reduce the computational burden.

**Fundamental Trade-offs in Robust Control with Heterogeneous Uncertainty**  
Tamer Basar, University of Illinois at Urbana-Champaign

The paradigm of networked control systems, where the feedback loop is closed over heterogeneous networks, has opened up a vast number of opportunities for applications in different fields while creating also a number of challenges with regard to reliability, robustness, and security of control operations. This talk will address these challenges, where networks providing sensor measurements to controller(s) and those carrying control signals to the plant as well as the plant itself are vulnerable to stochastic as well as adversarial disturbances and sporadic failure of channel connectivity. The question of interest is the extent to which the plant, measured in terms of a performance metric, can tolerate such disturbances and failures, which themselves are also quantified in terms of some appropriate metrics.

Following a general overview of networked control problems, the talk will focus on linear-quadratic systems, with norm-bounded deterministic (adversarial) disturbance inputs and hybrid stochastic uncertainty that impacts network channels, which is characterized by additive Gaussian noise and Bernoulli type failures. Explicit results for both the estimation problem and the control problem will be discussed under the TCP (Transmission Control Protocol) type information structure (which leads to certainty-equivalence, but not to separation of estimation and control), and the trade-offs between control performance, disturbance energy, and channel failure rates (that is, channel reliability) will be quantified. Under the UDP (User Datagram Protocol) type packet loss acknowledgement process, on the other hand, there is no certainty-equivalence, but still some trade-off results can be obtained. The talk will conclude with a discussion of future directions of research in this area and the challenges that lie ahead.

(This is based on joint work with Jun Moon)

**On the Role of Public and Private Assessments in Security Information Sharing Agreements**  
Mingyan Liu (and Parinaz Naghizadeh), University of Michigan

In recent years, sharing of security information among organizations, particularly information on both successful and failed security breaches, has been proposed as a method for improving the state of cybersecurity. However, there is a conflict between individual and social goals in these agreements: despite the benefits of making such information available, the associated disclosure costs (e.g., drop in market value and loss of reputation) act as a disincentive for firms’ full disclosure. This talk will present a game theoretic approach to understanding firms’ incentives for disclosing their security information given such costs. We propose a repeated game formulation of these interactions, which enables the design of inter-temporal incentives (i.e., conditioning future cooperation on the history of past interactions). Specifically, we show that a ratings/assessment system can play a key role in enabling the design of appropriate incentives for supporting cooperation among firms. We further show that in the absence of a monitor, similar incentives can be designed if participating firms are provided with a communication platform, through which they can share their beliefs about others’ adherence to the agreement.

**Resilient Vehicle Localization Using Vehicular Networks and Infrastructure**  
Heath LeBlanc, Ohio Northern University

Precise and accurate localization of vehicles is a critical problem in a variety of Intelligent Transportation System (ITS) applications including vehicle navigation, automated maneuvers, and vehicle tracking. Although the Global Positioning System (GPS) has been a widely employed solution for localization application services, highly precise and accurate GPS-based localization solutions are typically expensive. Hence for applications requiring greater accuracy and precision, low-cost solutions are needed. Furthermore, given the growing threat of cyber-attacks, resilient protocols...
are needed that can guarantee a baseline of performance even in the event of a cyber-attack. In this presentation, we present a resilient distributed algorithm that combines GPS, odometer, and digital compass measurements with position estimates from other vehicles and roadside units for a cooperative approach to localization. The proposed localization approach uses a piecewise constant-velocity model of the vehicle to significantly increase the sampling rate of the localization algorithm, so that it is not constrained by the low sampling rate of the GPS (i.e., 10 Hz). This enables greater localization accuracy at high speeds. Finally, redundancies in the vehicular ad hoc network are used to enable resilience in spite of unidentified malicious vehicles that have been hijacked by a hacker. The proposed localization approach is tested in various simulated highway scenarios using the NS3 network simulator to simulate the IEEE 802.11p communication standard for vehicular networks. The proposed approach is able to achieve sub-meter localization accuracy at high speeds (100 km/hr) and is demonstrated to be resilient to a class of cyber-attackers. The approach is suitable for open highway conditions, where multipath error due to loss of line of sight of GPS satellites is not prevalent.

Resilient Stabilization Against Adversarial Switching with Applications to Networked Control Systems
Jianghai Hu, Purdue University

The resilient stabilization problem for discrete-time switched linear systems is a dynamic game between two players: the user controls the continuous input and tries to stabilize the system, whereas an adversary controls the switching and tries to destabilize the system. Depending on which player moves first, two information structures are considered. In each case, the stabilizability of the systems is studied quantitatively using (extremal and Barabanov) norms, and marginal stabilizability is characterized using the notions of nondefectiveness and irreducibility. Computation algorithms as well as applications to networked control systems will be presented.

Automatic Formal Synthesis of Distributed Cooperative Systems
Hai Lin, University of Notre Dame

A common challenge in our future engineered system design, such as power grids, intelligent transportation networks and Internet of Things, is how to make a large number of distributed systems work together in a reliable and efficient manner. Existing methods are either only suitable for small scale systematic synthesis, oversimplifying the nodal dynamics, lack of performance guarantees or fail to adapt to changing environments. This motivates our research aiming at a scalable, correct-by-construction formal design methodology for distributed cooperative systems. In particular, we focus on a formal design of multi-robot systems that can guarantee the accomplishment of high-level team missions through automatic synthesis of local coordination mechanisms and control laws. Our basic idea is to decompose the team mission into individual subtasks such that the design can be reduced to local synthesis problems for individual robots, and then solving these local synthesis problems by composing predesigned and verified reactive motion/action primitives of robots. Multidisciplinary approaches combining control theory, machine learning and computational verification are utilized to achieve this goal. The developed theory will enable robots in the team to cooperatively learn their individual roles in a mission, and then automatically synthesize local task and mission plans to fulfill their subtasks. A salient feature of the proposed method lies on its ability to handle environmental uncertainties and un-modeled dynamics, as we do not require an explicit model of the transition dynamics of each agent and their interactions with the environment. In addition, the design is on-line and reactive enabling the robot team to adapt to changing environments and dynamic tasking.

Bridging Gaps Between Theory and Practice in Adaptive Control
Jonathan Muse, Air Force Research Laboratory

In aerospace control applications, there are often high standards set in order to certify a control law for flight. Unfortunately, most nonlinear control theory developed tends to ignore many of the typical concerns that make it difficult to confidently apply a new theory. Direct adaptive
control methods are no different. Recently, some interesting theoretical progress has been made towards answering many of the practical concerns about using direct adaptive control. We are starting to be able to answer questions related to things such as actuator bandwidth requirements, enforcing state limits, stability of sequential loop closure architectures, robust architectures for unmodeled dynamics, and systematic methods for designing output feedback adaptive control laws. This presentation will attempt to motivate why these issues are perceived to be important while discussing our recent developments.

Hypothesis Testing: Stochastic Approximation Point of View
Angelina Nedic, University of Illinois at Urbana-Champaign

We will consider the problem of hypothesis testing and related the Bayesian rule to a stochastic approximation for a suitably defined optimization problem. We will examine asymptotic behavior and non-asymptotic convergence rate properties for a centralized hypothesis testing problem. Then, we would discuss the extensions of these results to distributed cooperative learning in a network of agents, where the agents are repeatedly gaining partial information about an unknown random variable whose distribution is to be jointly estimated. Additionally, we provide a new non-Bayesian learning protocol that converges an order of magnitude faster than the learning protocols currently available in the literature for arbitrary fixed undirected graphs.

On the Structural Controllability of Sparse Bilinear Systems
Ali Belabbas, University of Illinois at Urbana-Champaign

Bilinear control systems exhibit the simplest form of couplings between the state of the system and control inputs, and as such retain part of simplicity of analysis of linear systems, while capturing the more complex behavior of nonlinear control systems. The controllability bilinear systems is a well-studied topic, although there are still many open questions about their most basic controllability properties. We present in this talk some recent results on the structural controllability of the class of driftless sparse bilinear control system, where the control matrices are forced to be of certain sparse patterns; some entries are fixed to zero and other are arbitrary real. We prove that sparse bilinear control systems are structurally controllable, hence extending a classical result of Boothby and Wilson to the class of sparse bilinear control systems. We then relate the sparse pattern of the matrices, the controllability of the system and some properties of graphs associated to said patterns.

A Distributed Semi-Cooperative Coordination Protocol for Dynamic Multi-Agent Systems
Dimitra Panagou, University of Michigan

Control of multi-agent systems and networked agents has been a popular topic of research with applications in numerous real-world problems involving autonomous unmanned vehicles and robotic assets. Planning, coordination and control for such complex systems is challenging due to the agents’ dynamics, their restrictions in onboard power, sensing, communication and computation capabilities, the number of agents in the network, and uncertainty about the environment. In this talk we will present some of our recent results on the distributed semi-cooperative motion planning and coordination for multiple mobile agents that belong in different classes, defined in terms of their sensing/communication constraints and/or priorities. The proposed protocol achieves the on-the-fly prioritization among connected agents and preserves safety guarantees for the network with not all of the agents participating in conflict resolution and collision avoidance.

Distributed Nonconvex Multiagent Optimization over Time-varying Networks
Gesualdo Scutari, Purdue University

Nowadays, large-scale systems are ubiquitous. Some examples/applications include wireless communication networks; electricity grid, sensor, and cloud networks; and machine learning and signal processing applications, just to name a few. In many of the above systems, i) data are distributively stored in the network (e.g., clouds, computers, sensors, robots), and ii) it is often impossible to run analytics on central fusion centers, owing to the volume of data, energy constraints, and/or privacy issues. Thus, distributed in-network processing with parallelized multi-processors is preferred. Moreover, many
applications of interest lead to large-scale optimization problems with nonconvex, nonseparable objective functions. All this makes the analysis and design of distributed/parallel algorithms over networks a challenging task. In this talk we will present our ongoing work in this area. More specifically, we consider a large-scale network composed of agents aiming to distributively minimize a (nonconvex) smooth sum-utility function plus a nonsmooth (nonseparable), convex one. The latter is usually employed to enforce some structure in the solution, e.g., sparsity. The agents have access only to their local functions but not the whole objective, and the network is modeled as a directed, (possibly asymmetric) time-varying graph. We propose a distributed solution method for the above optimization wherein the agents in parallel minimize a convex surrogate of the original nonconvex objective while using push-sum-based protocols to broadcast information over the network. Convergence to stationary solutions is established. We discuss several instances of the general algorithm framework tailored to specific (convex and nonconvex) applications and present some numerical results validating our theoretical findings.

### Student/Postdoc Session 1

#### (RAWLS 1086)

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<thead>
<tr>
<th>Title</th>
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<tr>
<td><strong>A Game-Theoretic Method for Multi-Period Demand Response: Revenue Maximization, Power Allocation, and Asymptotic Behavior</strong>&lt;br&gt;Khaled Alshehri, University of Illinois at Urbana-Champaign</td>
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<td><strong>Impact of Community Structure on Cascade</strong>&lt;br&gt;Mehrdad Moharrami, University of Michigan</td>
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<td><strong>Impact of crowdsourcing tournament design on design outcomes</strong>&lt;br&gt;Murtuza Shergadwala, Purdue University</td>
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In this work, we study a multi-period demand response problem in which utility companies aim to maximize their revenues and users aim to maximize their individual payoffs. We formulate a power allocation game for utility companies. The game is shown to have a unique pure-strategy Nash equilibrium at which the revenues are maximized, and a closed-form solution is provided. We study the asymptotic behavior of the equilibrium strategies when the number of periods and the number of users are large. We also derive an appropriate company-to-user ratio for the large population regime.

**Impact of Community Structure on Cascade**

Mehrdad Moharrami, University of Michigan

The threshold model is widely used to study the propagation of opinions and technologies in social networks. In this model individuals adopt the new behavior based on how many neighbors have already chosen it. We study cascades under the threshold model on sparse random graphs with community structure to see whether the existence of communities affects the number of individuals who finally adopt the new behavior. Specifically, we consider the permanent adoption model where nodes that have adopted the new behavior cannot change their state. When seeding a small number of agents with the new behavior, the community structure has little effect on the final proportion of people that adopt it, i.e., the contagion threshold is the same as if there were just one community. On the other hand, seeding a fraction of population with the new behavior has a significant impact on the cascade with the optimal seeding strategy depending on how strongly the communities are connected. In particular, when the communities are strongly connected, seeding in one community outperforms the symmetric seeding strategy that seeds equally in all communities.

**Impact of crowdsourcing tournament design on design outcomes**

Murtuza Shergadwala, Purdue University

Game theory enables us to model strategic decision making of the participants in a tournament. Within the context of crowdsourcing scenarios, human factors and biases play an important role in determining the success of a crowdsourcing tournament. Specifically within design, understanding the impact of design decision making on design competitions poses unique challenges such as understanding of strategies in design processes, the variation of preference structures of the designer “crowd” and sequential decision making. In my research, I utilize game theoretic models to model strategic decision making of the participants. I also utilize behavioral experimentation to study the actual behavior of the participants. We hypothesize that such an approach could help us understand the impact of tournament design on design decision making and
thus on tournament outcomes specifically the design solution quality.

**Dynamic Games with Asymmetric Information: Common Information Based Perfect Bayesian Equilibria and Sequential Decomposition**

Hamidreza Tavafoghi, University of Michigan

We formulate and analyze a general class of stochastic dynamic games with asymmetric information arising in dynamic systems. In such games, multiple strategic agents control the system dynamics and have different information about the system over time. Because of the presence of asymmetric information, each agent needs to form beliefs about other agents' private information. Therefore, the specification of the agents' beliefs along with their strategies is necessary to study the dynamic game. We use Perfect Bayesian equilibrium (PBE) as our solution concept. A PBE consists of a pair of strategy profile and belief system. In a PBE, every agent's strategy should be a best response under the belief system, and the belief system depends on agents' strategy profile when there is signaling among agents. Therefore, the circular dependence between strategy profile and belief system makes it difficult to compute PBEs. Using the common information among agents, we introduce a subclass of PBEs called common information based perfect Bayesian equilibria (CIB-PBEs), and provide a sequential decomposition of the dynamic game. Such decomposition leads to a backward induction algorithm to compute CIB-PBEs.

**Fast Rates and Network Independence in Distributed Learning**

César A. Uribe, University of Illinois at Urbana-Champaign

Networks in which individuals share and aggregate information following local rules and communication constraints are known as ‘social networks.’ The objective is to achieve global behaviors by repeatedly aggregating local information without complete knowledge of the network. Although the name is reminiscent of human behavior, a network might well be made of sensors, robots or other engineered system. Several results along these themes have appeared in recent years, nonetheless the study of distributed decision making and computation can be traced back to the classic papers from the 70s and 80s. In this work we consider the problem of distributed learning where a network of agents repeatedly observe some random processes and would like to collectively agree on a hypothesis that best explains all the observations in the network. In addition agents also repeatedly receive information from their neighbors, defined over a time-varying sequence of graphs.

We present a sequence of distributed learning protocols and show they allow the network to learn the set of hypotheses which explain the data collected by all the nodes best (i.e. consistency). Moreover we provide geometric, non-asymptotic, and explicit characterization of their convergence rates, which immediately leads to finite-time bounds that scale intelligibly with the number of nodes. We consider specific protocols for static-undirected and time-varying (un)directed graphs. In the case of directed graphs we show that a push-sum inspired algorithm allows for network independent rates. For fixed undirected graphs we show the proposed protocol converges a factor of $n$ faster than previous algorithms. Finally, we show protocols with uniform social sampling reduce the amount of communication needed at each time step but reduces the converge rate in a factor inversely proportional to the number of hypothesis. Furthermore, a novel connection between distributed Bayesian learning and distributed stochastic mirror descent algorithms is introduced.

**Uncertainty Quantification in Power Grid**

Parth Paritosh, Purdue University

This work explores the effect of power consumption uncertainties for contingency analysis in power grid control. We aim to predict grid stability under demand uncertainty and compute limits on demand variation for stable operation. The uniqueness of power grid dynamics stems from geographical separation between generators and controllers, and decisions based on delayed synchrophasor output. A wide area network control model has been selected to represent transmission operators at interconnection level. Non-linear synchronous generator network and power flow equations have been simulated to observe transition between various equilibria under the effect of demand variation. Based on synchrophasor measurements, estimation based controllers are designed and
implemented on linearized systems. Real time load variation data at interconnection level is observed to model similar variations with Gaussian processes. Uncertainty originating from these processes is to be propagated through controlled network and compared with non-linear system simulation. Questions pertaining to grid security such as robustness to measurement data corruption can be quantified using similar approach.

**Strategic Communication in Multi-agent Systems with Applications in the Smart City**
Emrah Akyol, University of Illinois at Urbana-Champaign

This talk is about communication scenarios where the encoder and the decoder have conflicting objectives: we analyze the well-studied information disclosure problems in information economics through the lens of information and estimation theories. Building on our prior work, we study the strategic communication paradigm over a sensor network. Each sensor is strategic and aims to maximize its own objective which involves type and source random variables. The objective of the receiver is to minimize the estimation error associated with the source. Two channel models, orthogonal and coherent multiple access channel, and two notions of equilibrium, Nash and herding equilibria, are considered. The optimal communication strategies achieving these equilibria and pay-offs at the equilibria are characterized for both channel models. The effects of sensing noise, channel noise, sensor power and the channel model on the pay-offs at equilibrium, and on the optimal communication strategies are analyzed. Numerical results obtained via simulations confirming the theoretical findings are presented, and finally the impact of the obtained results on the design of smart cities is briefly discussed.

**Taxi Market Equilibrium with Third-party Hailing Service**
Xinwu Qian, Purdue University

With the development and deployment of new technologies, the oligopolistic taxi industry is transforming into a shared market with coexistence of both traditional taxi service (TTS) and app-based third-party taxi service (ATTS). The ATTS is different from TTS in both entry policy and fare setting, and brings competition into the market. To account for the revolution of the taxi industry, in this study, we analyze the characteristics of the TTS and ATTS, model the taxi market as a multiple-leader-follower game at the network level, and investigate the equilibrium of taxi market with competition (TMC Equilibrium). In particular, passengers are modeled as the leaders who seek to minimize their cost associated with taxi rides. Followers involve TTS and ATTS drivers, who compete for passengers to maximize their revenue. The network model captures selfish behavior of passengers and drivers in the taxi market, and we prove the existence of TMC Equilibrium for the proposed model using variational inequality formulations. An iterative algorithm is further developed to find the TMC Equilibrium, which corresponds to the strongly stationary point of the multi-leader-follower game. Based on numerical results, it is observed that fleet size and pricing policy are closely associated with the level of competition in the market and may have significant impact on total passenger cost, average waiting time, and fleet utilization.

**Student/Postdoc Session 2 (RAWLS 1057)**

**Stability of the Continuous-Time Altafini Model**
Ji Liu, University of Illinois at Urbana-Champaign

We consider the continuous-time Altafini model for opinion dynamics in which the interaction among a group of agents is described by a piecewise-constant switching signed digraph (or directed graph). Stability of the system described by the model is studied using a graphical approach. It is shown that for any sequence of repeatedly jointly strongly connected digraphs, without any assumption on the sign structure of the graphs, the system asymptotically reaches a consensus in absolute value, including convergence to zero and different types of bipartite consensus (or two-clustering). Necessary and sufficient conditions for exponential stability with respect to each possible type of limit states are provided. Specifically, under the assumption of repeatedly jointly strong connectivity, it is shown that (1) a certain type of two-clustering will be reached exponentially fast
for almost all initial conditions if, and only if, the
sequence of signed digraphs is repeatedly jointly
structurally balanced corresponding to that type of
two-clustering; (2) the system will converge to zero
exponentially fast for all initial conditions if, and
only if, the sequence of signed digraphs is
repeatedly jointly structurally unbalanced.

On Switching Stabilization for Continuous-Time
Switched Systems
Yueyun Lu, Ohio State University

This talk addresses switching stabilization
problems for continuous-time switched systems. The
first part is on the equivalent characterization
of switching stabilizability for switched linear
systems. We consider four types of switching
stabilizability defined under different assumptions
on the switching control input and various solution
notions for the discontinuous system. The most
general switching stabilizability is defined as the
existence of a measurable switching signal under
which the resulting time-varying system is
asymptotically stable. Discrete switching
stabilizability requires the time-domain switching
signal to be piecewise constant on intervals of
uniform length. In addition, switching stabilizability
can be defined in terms of state-feedback laws. We
consider feedback stabilizability in Filippov sense
(resp. sample-and-hold sense) as the existence of a
feedback law under which the closed-loop Filippov
solution (resp. sample-and-hold solution) is
asymptotically stable. We prove that for switched
linear systems, the four switching stabilizability
notions are equivalent and their sufficient and
necessary condition is the existence of a piecewise-
quadratic control-Lyapunov function that can be
expressed as the pointwise minimum of a finite
number of quadratic functions. The second part is
on the sufficient condition of feedback
stabilizability in Filippov sense for general switched
nonlinear systems. We propose a piecewise
smooth control-Lyapunov function approach to
construct stabilizing switching laws under which all
Filippov solutions including sliding motions are
stable. We point out various technical subtleties
arising on the nonsmooth surface of control-
Lyapunov function and discontinuous vector field
and show how the proposed condition handles
them in a unified way.

On the Stability of Conjunctive Boolean Networks
Zuguang Gao, University of Illinois at Urbana-
Champaign

Boolean networks have been used extensively in
modeling many biological systems. In this work, we
study the stability of conjunctive Boolean
networks, which consist of canalyzing functions
using only the logic AND operator. To analyze the
stability of such networks, we develop a method
that decomposes the wiring diagram into a number
of components each of which is an irreducible
subgraph. In particular, we show that the system
may switch from one limit cycle to another under
certain conditions, when one of the variables fails
to follow the coordinate function. It is also shown
that for conjunctive Boolean networks whose
wiring diagram is strongly connected, the number
of limit cycles can be computed using the binary
necklace model.

Fuel optimal vehicle longitudinal control design
with optimality in gear shift
Junbo Jing, Ohio State University

This work introduces a vehicle speed controller
design with minimum fuel objective and the
capability of triggering gear shift optimally under
Model Predictive Control (MPC) framework. The
controller is required to seek the optimal control
trajectory of torque request and brake force in real
time for a given preceding vehicle speed
prediction. For a fixed gear selection, the problem
can be formulated into a classic Quadratic
Programming (QP) optimization problem.
However, with a 6-speed discrete ratio gearbox
engaged, the vehicle model becomes a switched
system with model parameters shift each time
when the gear selection is changed. In this case,
the optimality seeking process is hard to solve
numerically and highly time consuming. To achieve
the computation speed required for real-time
MPC, we developed a deduction method to
partition the complicated original problem into a
series of simplified sub-problems. Fast quasi-
optimal solutions are given to the simplified sub-
problems using an optimal driving pattern derived
by Pontryagin Minimum Principle (PMP). Search
space for the optimum is thus quickly and effective
narrowed down, till only a small number of gear
sequence combinations need to be numerically
searched for global optimality. This technique
efficiently reduces the problem into solving a few
simple QP optimizations that are light in computation. Problem partitioning method is summarized in a Finite State Machine (FSM) for all possible speed scenarios. Optimality in results is verified by enumerating through all feasible gear sequences. A simulation test shows that the developed controller can lead to a 14% fuel saving benefit with ride comfort ensured.

Safety Control Using Control Sharing Barrier Functions
Xiangru Xu, University of Michigan

Safety critical systems involve the tight coupling between potentially conflicting control objectives and safety constraints. When the safety specifications are represented as the forward invariance of a set, control barrier functions can be combined with control Lyapunov functions in a quadratic program to synthesize the safety controller. This paper investigates the control sharing property of control barrier functions with general relative degrees, which guarantees the existence of a common control so that multiple safety constraints can be satisfied simultaneously. These results are applied to the safety control of strict feedback nonlinear systems with time-varying output constraints.

Computing the distance to the nearest SMS unobservable switched LTI system
Scott C. Johnson, Purdue University

Reference [1] sets forth conditions for a switched linear time-invariant (SLTI) state model to move from a safe mode of operation to a failure mode (e.g. medical monitoring). Subsequently, [2] presents Frobenius-norm bounds on the smallest real perturbations to SLTI system matrices which result in an undetectable safe-to-fail mode transition. These results build on the problem of bounding the smallest perturbation that causes an observable system to become unobservable. However, an algorithm computing the exact distance and associated minimizing perturbation was not presented. This talk addresses this robust observability metric for SLTI state models and an algorithm for computing the smallest perturbation causing unobservability. SLTI state models consist of a dynamical state and a finite set of discrete modes of operation. For medical monitoring systems, the discrete modes of operation can represent safe and faulty system behavior, which is an uncontrolled and unmeasured input. State and mode sequence (SMS) observability answers the question of feasibility of reconstructing the initial state and complete mode sequence from output measurements, and thus detecting mode transitions from safe to fail. The metric used in this work is the Frobenius norm of structured additive perturbations to the system matrices causing SMS unobservability. The descent algorithm for finding the distance to the nearest SMS unobservable SLTI system computes the smallest real, additive perturbations causing SMS unobservability by converging to a set of necessary conditions presenting in [3]. The algorithm is illustrated using the example presented in [2], where the result is shown to lie within the bounds computed in [2].


3D Underactuated Walking: Implementation of Gait Libraries
Xingye Da, University of Michigan

Analysis and controller design methods abound in the literature for planar (aka 2D) bipedal models. This work takes one of them developed for underactuated bipeds, documents the process of designing a family of controllers as a gait library and achieves stable walking on a physical 3D robot, both indoors and outdoors, with walking speed varying smoothly from 0 to 0.8 meters per second. The experiment has several remarkable records versus peers: 260 meters continuously outdoor walking, 7 degree maximum up and down hill, turning (yaw), walking on grass and snow.

Cluster Consensus over Strongly Connected Voltage Graphs
Xudong Chen, University of Illinois at Urbana-Champaign
A cluster consensus system is a multi-agent system in which the autonomous agents communicate to form multiple clusters, with each cluster of agents asymptotically converging to the same clustering point. We introduce in this paper a special class of cluster consensus dynamics, termed the G-clustering dynamics for $G$ a point group, whereby the autonomous agents can form as many as $|G|$ clusters, and moreover, the associated $|G|$ clustering points exhibit a geometric symmetry induced by the point group. The definition of a G-clustering dynamics relies on the use of the so-called voltage graph. We recall that a G-voltage graph is comprised of two elements—one is a directed graph (digraph), and the other is a map assigning elements of a group $G$ to the edges of the digraph. For example, in the case when $G = \{1, -1\}$, i.e., a cyclic group of order 2, a voltage graph is nothing but a signed graph. A G-clustering dynamics can then be viewed as a generalization of the so-called Altafini’s model, which was originally defined over a signed graph, by defining the dynamics over a voltage graph. One of the main contributions of this paper is to identify a necessary and sufficient condition for the exponential convergence of a G-clustering dynamics. Various properties of voltage graphs that are necessary for establishing the convergence result are also investigated, some of which might be of independent interest in topological graph theory.

**Student/Postdoc Session 3 (RAWLS 1086)**

**Interdependent Security Games on Networks under Behavioral Probability Weighting**

Ashish R. Hota, Purdue University

We consider a class of interdependent security games on networks where each node chooses a personal level of security investment. The attack probability experienced by a node is a function of her own investment and the investment by her neighbors in the network. Most of the existing work in these settings consider players who are risk neutral or expected value maximizers. In contrast, studies in behavioral decision theory have shown that individuals often deviate from risk neutral behavior while making decisions under uncertainty. In particular, the true probabilities associated with uncertain outcomes are often transformed into perceived probabilities in a highly nonlinear fashion by the users, which then influence their decisions. In this work, we investigate the effects of such behavioral probability weightings by the nodes on their optimal investment strategies and the resulting security risk profiles that arise in the Nash equilibria of interdependent network security games. We characterize graph topologies that achieve the largest and smallest worst case average attack probabilities at Nash equilibria in Total Effort games, and equilibrium investments in Weakest Link and Best Shot games.

**A Resilient Design for Cyber Physical Systems under Attack**

Yang Yan, University of Notre Dame

Cyber physical systems feature a tight coupling of cyber infrastructure used for transmission and processing of data, and physical components that are being controlled. Applications of such an architecture span many domains, including infrastructure systems such as the power grid, transportation networks, and civil infrastructure. However, one challenge for this architecture is the possibility of a malicious intruder to change the data transmitted across the cyber channel as a means to degrade the performance of the physical system. Accordingly, security of cyber physical systems needs to be thought through and designed carefully. In this talk, we consider a data injection attack on a cyber physical system. We model the system as a hybrid system and propose a joint framework for detecting the presence of an attack and operating the plant in the presence of an attack. Our method uses an observer based detection mechanism and the minimax interpretation of H-infinity control; however, in a hybrid automaton framework. Global exponential stability is established under the proposed framework.

**Reaching approximate Byzantine consensus with multi-hop communication**

Lili Su, University of Illinois at Urbana-Champaign

We address the problem of reaching approximate consensus in the presence of Byzantine faults in a
synchronous system. We analyze iterative algorithms that maintain minimal state, and impose the constraint that in each iteration the nodes may only communicate with other nodes that are up to \( l \) hops away. For a given \( l \), we prove a necessary and sufficient condition on the network structure for the existence of correct iterative algorithms that achieve approximate Byzantine consensus. We prove sufficiency of the condition by designing a correct algorithm, which uses a trim function based on a minimal messages cover property introduced in this paper. Our necessary and sufficient condition generalizes the tight condition identified in prior work for \( l=1 \). For \( l \geq l^* \), where \( l^* \) is the length of a longest cycle-free path in the given network, our condition is equivalent to the necessary and sufficient conditions for exact consensus in undirected and directed networks both.

**Improved Sensor Fault Detection, Isolation, and Mitigation Via Integrating New Methods Into An Existing Residual-Based Method**
Zheng Wang, University of Michigan

Sensor faults in physical systems can result in integrity damage and/or degradation of control system performance. To detect sensor faults, traditional Fault Detection and Isolation (FDI) methods can be used to analyze a residual signal, where the residual signal is formed by the difference between the sensor measurements and the estimated output of the system based on an observer. The traditional residual-based FDI methods, however, have some limitations. First, they require that the observer has reached its steady state when a fault starts. In addition, residual-based methods may not detect some sensor faults, such as faults on critical sensors caused by some cyber attacks that render the system to be not observable. Furthermore, the system may be in jeopardy if actions required for mitigating the impact of the faulty sensors are not taken before the faulty sensors are located. The contribution of this paper is to propose three new methods based on multiple observers for observable systems to address these limitations by: 1) enabling sensor fault detection and reduce false alarms during the observers transient state; 2) detecting faults on critical sensors; 3) potentially mitigating the impact of the faulty sensor during the FDI process. These three methods are systematically integrated with a previously developed residual-based method to provide a complete FDI and mitigation capability. The overall approach is validated mathematically. We illustrate the effectiveness of the overall approach on a 5-state suspension system in simulation.

**Bi-Virus SIS Model: Analysis and Control**
Philip E. Paré, University of Illinois at Urbana-Champaign

The spread of epidemic processes over large populations is an important research area, and is in fact a widely studied topic in epidemiology. In this work we focus on continuous time susceptible-infected-susceptible (SIS) models. Such models consist of a number of agents that are either infected or healthy (susceptible), and cycle back and forth between these two states depending on their current state, connection to infected neighbors, and infection and healing rates. This model can be extended to the competing virus case, where each agent can be infected with either virus or is susceptible to infection, and each virus propagates over a different network. One of the primary motivations for studying these systems has been to understand how competing opinions spread on different social networks. Most of the previous work has been conducted for undirected graph structures with limited/local stability analysis.

In this talk, I will present work where we study a distributed continuous-time bi-virus model over directed graphs. I will present an in-depth analysis of the equilibria of the bi-virus model over directed graphs and their stability under appropriate conditions, including necessary and sufficient conditions for the disease free equilibrium. I will also present results on the existence and stability of the epidemic equilibrium states, which include the dominant-virus and co-existence cases. One particular case will be expounded upon, where if the two viruses propagate over the same network, under certain conditions, the equilibrium of one virus is equal to a scaled version of the equilibrium of the other virus. These results will be supported by illustrative simulations. I will also present an interesting and surprising impossibility result for a distributed feedback controller.
Secure Distributed Observers for a Class of Linear Time Invariant Systems in the Presence of Byzantine Adversaries
Aritra Mitra, Purdue University

The problem of distributed state estimation for LTI systems has been widely studied over the past decade. However, the literature dealing with secure estimation strategies in the face of adversarial attacks on the individual observers is relatively new and limited. In this work, we develop a secure distributed estimation strategy subject to an f-locally bounded Byzantine adversary model, where a compromised node is given complete knowledge of the network and system dynamics, and allowed to arbitrarily deviate from any prescribed algorithm. Under such a threat model, we furnish sufficient conditions guaranteeing the success of our estimation strategy. Our method relies on the construction of a subgraph, which we call a Mode Estimation Directed Acyclic Graph (MEDAG), for each unstable eigenvalue of the plant. We provide a distributed algorithm for constructing a MEDAG, and also characterize graph topologies for which a MEDAG construction algorithm is guaranteed to succeed. In the process, we make connections with the literature on secure broadcasting. In the special case where there are no adversaries, our proposed method provides a new class of distributed observers with several appealing features. Our approach provides fundamental insights into the relationship that exists between the dynamics of the system, the measurement structure of the nodes, and the underlying graph topology.

Conformity versus Manipulation in Reputation Systems
Sadegh Bolouki, University of Illinois at Urbana-Champaign

In a reputation system, the public opinion about an object is assessed by a score between 0 and 1, based on the opinions of individuals within a community. Each individual expresses an opinion, modeled by a scalar in the interval [0,1], about that object and the object’s score is determined as the arithmetic mean of all opinions. Individuals may not express their actual opinions, which are assumed to be fixed, for a variety of reasons. In this talk, we address in a unified, game-theoretic framework the influence of two opposing social behaviors, namely conformity and manipulation, on the outcome of a reputation system. For the purposes of this talk, conformity as a social behavior refers to the tendency of an individual to express an opinion that matches the public opinion, whereas manipulation refers to the tendency of an individual to express an opinion so as to manipulate the public opinion towards her actual opinion.

Student/Postdoc Session 4
(RAWLS 1057)

Strategic Control of a Tracking System
Muhammed O. Sayin, University of Illinois at Urbana-Champaign

We consider stochastic dynamic game problems where a trajectory controller takes an action to construct an information bearing signal, namely the control input, and subsequently a tracking system takes an action, i.e., constructs a tracking output, based on the control input. The trajectory controller has access to two Gaussian processes evolving according to first order autoregressive models, e.g., desired and private states. Different from the design of a measurement or sensing scheme for a tracking system, here the trajectory controller and the tracking system have different objectives such that the trajectory controller aims the tracking output to track sum of the desired and private states while the tracking system constructs the output to track the desired state only. For finite horizon problems involving two different quadratic cost functions, we show that the optimal control input policies are linear functions of the current states when the states evolve in parallel. We then extend this result for the general case when the trajectory controller has a myopic objective and show that the optimal control input policies are also linear functions of the current states. Finally, we restrict the policy space for the control input to the set of all linear mappings of the current states and convert the finite horizon stochastic game problem into a discrete time deterministic optimal control problem. We also include some illustrative numerical examples for different strategic control scenarios.
Visibility-based Target Tracking in Polygonal Environments
Hamid Emadi, Iowa State University

In this presentation, I will talk about a visibility-based pursuit-evasion game that arises between mobile guards and a mobile target in bounded simply connected polygonal environments. The results will leverage on techniques from art-gallery problems in computational geometry, and optimal control theory. I will consider two scenarios, namely, open-loop and closed-loop strategy for the guards. In the class of closed-loop strategies, I will propose a deployment and motion strategy for a group of static and mobile guards to guarantee infinite tracking time for the target. In the class of open-loop strategies, I will present optimal strategy for the guards when the polygon has one reflex vertex. The results are extended to provide a guaranteed tracking time for the guards in general polygonal environments.

Target Tracking using Multiple Unmanned Aerial Vehicles
Bharathan, Purdue University

This paper develops a control algorithm for multiple UAVs to track a moving target with the consideration of the presence of obstacles that might hinder the tracking of the target. The motion of the target is modeled by a dynamic occupancy grid. It is assumed that at least one UAV are able to measure the target's position with a certain probability. The algorithm utilizes a linear combination of all UAVs' measurements and a finite look-ahead path selection in order to maximize the detection probability of the target. In the worst case when only one UAV detects the target, all the other UAVs just follows this UAV and can still track the target. It has been analytically and experimentally shown that the proposed algorithm leads to a higher tracking probability than existing results.

Gain function Approximation in the Feedback Particle Filter
Amirhossein Taghvaei, University of Illinois at Urbana-Champaign

Feedback Particle Filter is a nonlinear filtering algorithm that was recently developed based on concepts form mean-field games and optimal control theory. The algorithm is a new formulation of the particle filter, that does not require resampling, and preserves the feedback structure of the Kalman filter. The main idea of the algorithm is to design a control law for a system of stochastic processes (particles), such that the empirical distribution of the particles approximate the underlying posterior distribution. The resulting control law has a feedback structure, i.e., innovation error multiplied by a gain function. The exact gain function is the solution of a Poisson equation involving a probability-weighted Laplacian. The problem is to approximate the gain function using only particles which are samples from the probability distribution (probability distribution is not explicitly known). The currently used approach is the Galerkin algorithm. In this talk I will discuss the limitations of the current approach and present a novel kernel-based algorithm that overcomes those limitations. The new algorithm is motivated by the construction of the Graph Laplacian in the spectral clustering methods. Finally I will provide error analysis for the algorithm and illustrate the performance with the aid of some numerical results.

A Geometric Approach to Virtual Battery Modeling of Thermostatically Controlled Loads
Lin Zhao, Ohio State University

A large population of thermostatically controlled loads (TCLs) can be coordinated to provide various ancillary services to the grid. Effective operation and coordination of TCLs requires an accurate and simple model to capture their aggregate power flexibility. One appealing approach is the virtual battery method, which models the aggregate flexibility offered by a collection of TCLs as a simple scalar dynamical system that resembles the dynamic behavior of a battery with limits on the energy capacity and the output power. In this paper, we propose a novel geometric approach to design a virtual battery model for a given TCL population. We adopt a discrete time formulation of the individual TCL dynamics over a finite time-horizon. This allows for a clear geometric interpretation of the individual flexibility, which is shown to be a polytope. The aggregate flexibility can be represented by the Minkowski sum of the individual polytopes. In view of the special structure of these polytopes, we further propose two design methods to optimally extract each TCL’s flexibilities, both via approximating the polytope with respect to the scaling and translation of a
given polytope. The optimal scaling and translation factors are solved efficiently from equivalent linear programming problems. The aggregate flexibility is approximated by a virtual battery model obtained from an easy calculation of the Minkowski sum of those obtained similar polytopes. Simulation results show significant improvement and superior performance over the existing methods.

On Remote Estimation with Multiple Communication Channels
Xiaobin Gao, University of Illinois at Urbana-Champaign

This paper considers a sequential estimation and sensor scheduling problem in the presence of multiple communication channels. As opposed to the classical remote estimation problem that involves one perfect (noiseless) channel and one extremely noisy channel (which corresponds to not transmitting the observed state), a more realistic additive noise channel with fixed power constraint along with a more costly perfect channel is considered. It is shown, via a counter-example, that the common folklore of applying symmetric threshold policy, which is well known to be optimal (for unimodal state densities) in the classical two-channel remote estimation problem, is no longer optimal for the setting considered. Next, in order to make the problem tractable, a side channel which signals the sign of the underlying state is considered. It is shown that, under some technical assumptions, threshold-in-threshold communication scheduling is optimal for this setting. The impact of the presence of a noisy channel is analyzed numerically based on dynamic programming. This numerical analysis uncovers some rather surprising results inhering known properties from the noisy and noiseless settings.

Optimized Landing Algorithm for the Swarm of VTOL Airplanes
Lunaric Ko, Purdue University

This paper lays out a landing system of a swarm of Unmanned Aerial Vehicles (UAV) with collision avoidance. An optimal solution is proposed for minimizing the time of horizon and energy spent while hovering. The key idea is to conduct the computation of the numbers of possible landing events in descending order by the Mixed Integer Linear Programming (MILP) in real time followed by the Depth First Search (DFS). It then assigns the optimal solution to each airplane if the number of incoming airplanes is greater than the maximum number of possible concurrent landing events. If there are more than a set whose maximum number of concurrent landing event exceeds that of the incoming number of airplanes, then the program will place the airplanes to the set that has the minimal number of concurrent landing events out of the ones that exceed the number of the incoming airplanes in order to maintain the maximum number of concurrent landing event. A simulation has been conducted in time-varying case with 80 landing positions with some of them already being occupied initially. The minimal separation range is given to be 3 units as big as the size of the landing zone. Portion of them is to come intermittently to completely fill the landing zone.