2016 AFOSR Dynamic and Controls Annual Review Abstracts

Day 1 (Aug 2nd 2016):

Title: Pursuit-evasion games and application

Abstract: Two different pursuit-evasion games will be discussed. The first is a zero-sum differential game, involving 3-agents divided into two teams. One team consists of a Target (Evader) and Defender, and the other consists of the Attacker (Pursuer). The solution of this game provides a robust feedback policy that is easily computed. The second is a pursuer-evader game on a graph. Thee evader is restricted to travel on a road network (graph), where Unattended Ground Sensors (UGS) have been placed to detect and record movement of the evader. Unlike typical games of this nature, the pursuer's observation structure is constrained by the communication restrictions with respect to the UGS. The Pursuer has a goal to capture the Evader, which is accomplished by visiting the UGS and using these observations to track down the evader. Recent flight test experiments will be presented involving two UAVs using peer-to-peer coordination and on-board decision making to jointly pursue the evader.

Dr. David Casbeer, AFRL/RQ

Title: "Verifiable Human-Automation UAV Task Assignment and Scheduling Systems"

Abstract: The focus of this effort is the development of frameworks and algorithms that support verifiably correct behavior in human-automation mission planning systems for unmanned aerial vehicles (UAVs). Our approaches draw inspiration from model checking, one of two major classes of formal methods used for design and verification of hardware and software. In model checking, a system model is automatically checked against a set of specifications. If the model is capable of exhibiting at least one behavior that violates the specifications, a counterexample that demonstrates an erroneous behavior is returned to aid debugging of the model or refinement of the specifications; if the model is exhaustively checked and no counterexamples are found, then the model is verified to be correct. Alternatively, given a set of specifications, it is possible in some cases to synthesize a "correct-by-construction" system model. Similar capabilities for formulating mission goals and developing verifiably correct UAV mission plans have the potential to reduce errors and improve mission performance.

Toward this end, this effort has most recently focused on increasing the level of automation in human-automation UAV planning systems in such a way that mission specifications can be either guaranteed or verified. The level of automation is increased by providing automated tasks for waypoint-based UAV routing, e.g., that account for low-level details such as UAV dynamics and the geometry of the UAV sensor footprint or that can react non-deterministically or probabilistically at runtime to local information discovered in the mission environment. To generate guaranteed behaviors, we use approaches based on reactive synthesis from Generalized Reactivity (1) formulas. To enable more intuitive verification of mission plans comprised of tasks with probabilistic behaviors, we provide a method for generating "structured probabilistic counterexamples" that enforce an intuitive structure on the counterexample that is based on the UAV tasks.

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Dr. Michael J. Patzek, 711HPW/RHCI, 2210 8th Street, Room 122, WPAFB, OH 45433

Title: A Paradigm Shift in the Construction of Estimators and Controllers for Linear Dynamic Systems with Additive Cauchy Uncertainty

Abstract: A new class of implementable real-time vector-state estimators and stochastic controllers for linear dynamic systems with additive heavy-tailed Cauchy process and measurement noises are to be developed. The estimation methodology for a vector-state, linear dynamic system with additive Cauchy noises was addressed by developing a recursion for the analytic measurement update and propagation of the character function of the unnormalized conditional probability density function (ucpdf) of the state given the measurement history. Other than the Kalman filter, the current estimation paradigm that is based on the light-tailed Gaussian pdf, this Cauchy estimator stands alone in being the only other estimator for linear multi-variable systems, which has an analytic recursive structure. This Cauchy estimator resolves efficiently uncertainties due to an impulse in the measurement or process noises. In fact, in contrast to the Kalman filter, the conditional probability density function for the Cauchy system is not always unimodal.

When addressing the stochastic control problem for Cauchy noise, the conditional probability density function must be used. Reminiscent of the cost criterion for the linear-exponential-Gaussian control problem, a cost criterion is constructed using the conditional expectation of a product of Cauchy functional forms of quadratics of the state and control variables. Through a spectral transformation, the character function of the ucpdf is used explicitly to evaluate in closed form the conditional expectation in this cost criterion for the development of stochastic controllers, based on a model predictive structure. The cost criterion of this stochastic controller, although analytic, is not convex. Nevertheless, there is a strong relationship between the global optimum and the system parameters that will be exploited.

The currently available results for estimation and control entail significant analytical and numerical complexities due to the rich analytic form of the character function of the ucpdf, which produces a sum of terms that grows at each measurement update. Our primary goal is to determine implementable real-time vector-state estimators and stochastic controllers by using simplifications that are due to the fundamental structure of the algorithms. Approximations that will conserve the basic structure of the character function are sought, and will be implemented on current computational hardware, such as graphic processing units. Addressing the computational issues of the Cauchy estimators and controllers will produce a practical methodology for resolving the perennial engineering problem of handling outliers in the measurement and process uncertainties. For example, the three-state Cauchy controller should have significant impact on the performance of homing missile guidance system against agile adversaries.

Dr. Jason L. Speyer, UCLA

Title: Cooperation and Autonomy in Communication-Limited Environments

Abstract: This presentation introduces several distributed control strategies to achieve consensus among the agents of a networked system over some measure of the time coordination, that we call the coordination variables. Time-driven process depending on these variables achieve consensus when the coordination errors of these variables are maintained within specified values. This presentation emphasizes the different types of coordination and final temporal constraints that can be imposed on time-critical coordinated multi-agent systems. Additionally, the combination of several mathematical artifacts borrowed from Lyapunov and algebraic graph theory are used to prove the stability and guaranteed performance properties of some of the proposed time-critical coordination algorithms. This presentation briefly discusses several improvements in the convergence rates of the proposed algorithms based on observer-based augmentations of the communications graph. The formal mathematical background of these algorithms is accompanied with several applications, especially in the aerospace industry, where the proposed algorithms could be leveraged to achieve coordination with performance guarantees.

Dr. Naira Hovakimyan, UIUC

Title: Preparation of Pure Gaussian States via Linear Quantum Systems with a Given Structure

Abstract: This presentation considers the problem of constructing a stable linear quantum system such that at steady state, it will be in a given pure Gaussian state. Furthermore, restrictions are placed on the structure of the linear quantum system. The structures considered include a cascade structure, a locally dissipative structure in which the system has only local interactions with its environment, systems with diagonal passive Hamiltonian and a single dissipative channel, and systems with a passive Hamiltonian and with a single reservoir which acts only on a single site of the system. These structures are considered since they would be easier to implement experimentally than a general linear quantum system. In each case, the set of possible Gaussian pure states that can be achieved with that structure is characterized. Also, examples are given from quantum optics.

Dr. Ian Petersen, USNW and Dr. Matthew James, ANU

Title: Temporal-logic-constrained synthesis and verification without discretization

Abstract: Can we algorithmically synthesize temporal-logic-constrained controllers for dynamical systems with 50 continuous states? Using conventional methods based on discretization, the answer is ‘no’. Even the coarsest discretization would result in intractably large discrete state spaces.

We present a novel approach that avoids explicit discretization in synthesis. We investigate the synthesis of optimal controllers for continuous-time and continuous-state systems under temporal logic specifications. We consider a setting in which the specification can be expressed as a deterministic, finite automaton (the specification automaton) with transition costs, and the optimal system behavior is captured by a cost function that is integrated over time. Specifically, we construct a dynamic programming problem over the product of the underlying continuous-time, continuous-state system and the discrete specification automaton. This dynamic programming formulation relies on the optimal substructure of the additive transition costs over the product of the system and specification automaton. Furthermore, we propose synthesis algorithms based on approximate dynamic programming for both linear and nonlinear systems under temporal logic constraints. We show that, for linear systems under co-safe temporal logic constraints, this approximate dynamic programming solution reduces to a semidefinite program.

As time allows, we overview a similar approach for the dual problem of verification of dynamical systems against temporal logic specifications. This approach combines automata-based verification and the use of so-called barrier certificates.

Dr. Ufuk Topcu, University of Texas (Austin)

Title: Computation-based Probabilistic Validation of Complex Cyber-controlled Systems

Abstract: This program is focused on a computational approach to verification of the hybrid mathematical models formed when combining physics-based models with discrete-transition models, such as those which model software algorithms; namely, the types of models that arise when physical processes are interconnected with digital hardware. The technical foundation for the program is the use of Markov process formulations, simulation, and probabilistic model checking to achieve a unified verification approach by leveraging the two large bodies of work on probabilistic analysis of purely physics-based models, and probabilistic model checking for purely discrete-transition systems. We present a new framework for considering automated analysis and validation of these systems using Markov chain models of ODEs and PDEs, coupled with spatio-temporal logics. A central aspect of the reported research is the development of probabilistic model checking algorithms and sophisticated abstraction techniques, and logics and algorithms to specifically reason about spatio-temporal system properties. Additionally, we are pursuing generalizations of these techniques for real-time situations where there are measurements available.

In particular, we report on new a method for verifying continuous-time stochastic hybrid systems (CTSHSs) via model reduction, whose behaviors are specified by metric interval temporal logic (MITL) formulas. By partitioning the state space of the CTSHS and computing the optimal transition rates between partitions, we provide a procedure to both reduce a CTSHS to a continuous-time Markov chain (CTMC), and the associated MITL formulas defined on the CTSHS to MITL specifications on the CTMC. We prove that an MITL formula on the CTSHS is true (or false) if the corresponding MITL formula on the CTMC is robustly true (or false) under certain perturbations. In addition, we propose a stochastic algorithm to complete the verification. As an example, we have also applied the framework to a research community benchmark, providing the first explicit verification results for this complex model (Toyota powertrain control verification benchmark). Specifically, we statistically verify the most complicated of the powertrain control models proposed, which includes features like delayed differential and difference equations, look up tables, and highly nonlinear dynamics. These are the first verification results for this model, statistical or otherwise.

Drs. Geir E. Dullerud (PI), Mahesh Viswanathan, and Matthew West, University of Illinois at Urbana-Champaign

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Title: Minimal Representation and Decision Making for Networked Autonomous Agents

Abstract: This project addresses fundamental issues that arise in information representation architectures for autonomous reasoning and learning, decentralized planning, and decision-making in multi-agent systems. The overall goal of the project is to develop efficient and adaptive strategies to process, represent, exchange, and act upon relevant information from massive data collections, much of which can be irrelevant, imprecise, and contradictory. Minimalism is at the core of the technical approach: this idea concerns the proper identification of the required information needed to achieve a given task with a desired performance level and provable performance guarantees. Minimal representations involve how appropriate models should be selected, how uncertainty should be managed, and how information should be represented, decomposed and communicated. Key role within this framework play set based approaches in order to perform information decomposition and synchronization for distributed filtering, and representation for meta-reasoning and coordination.

In particular, we study the problem of multi-robot target assignment to minimize the total distance traveled by the robots until they all reach an equal number of static targets. We present a necessary and sufficient condition under which true distance optimality can be achieved for robots with limited communication and target-sensing ranges. We also concentrate on the discrete-time Distributed Bayesian Filtering (DBF) algorithm for the problem of tracking a single target using a time-varying network of heterogeneous sensing agents. In the DBF algorithm, the sensing agents combine their normalized likelihood functions using the logarithmic opinion pool and the discrete-time dynamic average consensus algorithm. The convergence, stability, and robustness properties of the DBF algorithm are rigorously characterized.

Drs. Petros Voulgaris and Soon-Jo Chung, University of Illinois at Urbana-Champaign

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Title: Multi-Agent Control

Abstract: We consider the problem of designing effective optimization protocols enabling groups of cooperating agents to operate autonomously with only intermittent human supervision. Our main focus is the problem of effective formation maintenance, though we study a general framework of distributed optimization which encompasses other problems such as optimal positioning, task assignment, estimation, and resource allocation.

Our focus is on protocols which perform well even in the presence of faults, noise, fluctuating number of agents, or other changes in the environment. These issues present challenges for many state-of-the-art

protocols, which can handle them well in networks of only a few agents but have problems scaling up beyond that.

We propose new protocols to overcome these issues. In particular, (i) we design protocols for distributed optimization and formation control which converge fast on any network and whose performance scales gracefully with network size (ii) we give a complete characterization of the resiliency of undirected formations to noise, allowing us to recommend formations which can scale up to many agents.

Alex Olshevsky
UIUC

Title: Control & Estimation in the Presence of Adversarial Action and Uncertainty

Abstract: The solution of Linear-Quadratic Gaussian Dynamic Games (LQGDGs) where the players have partial information has been a longstanding goal of the controls and games communities. LQGDGs with a non-classical information pattern can be problematic, as Witsenhausen's counterexample illustrates. The state of affairs concerning dynamic games and dynamic team problems with partial information is not satisfactory. In this talk LQG Dynamic Games with a Control-Sharing Information Pattern will be discussed. The partial information pattern discussed herein is as follows. The players' information on the initial state and their measurements are private information, but each player is able to observe the antagonist's past inputs: the protagonists' past controls is shared information. This information pattern has previously been discussed in [1], and in the specific context of a team decision problem, it has been discussed in [2]. However, in [1] the author took "a wrong turn": as so often happens in the literature of games with partial information, one is tempted to assume the players will try to second guess the opponents' private information, say, the opponent's measurements. The vicious cycle of second guessing the opponent's measurements leads to a mirror gallery like setting and to a dead end. This point will be discussed in our talk. In reference [2] a decentralized dynamic team problem with a control-sharing information pattern is considered: It is argued that an infinite amount of information is contained in a real number, which, in theory, is correct. And since the control information is shared, then at least in a cooperative control/team setting, a player/agent could in principle encode in the controls information about to be sent to his partner his private information, for example, his measurements history. This is due to the fact that the controls which are about to be communicated can be modified slightly to encode the measurements information of the protagonists without significantly disturbing the control, and consequently, have a barely noticeable effect on the value of the game. One then falls back on the solution of the LQG cooperative control problem with a one-step-delay shared information pattern where also the past measurements are shared. However, this scheme has no place in a non-cooperative scenario, a.k.a., "zero-sum" LQGDG as discussed in our talk, and also does not properly model a decentralized control scenario. Moreover, this scheme totally depends on the players' ability of obtaining a noiseless observation of the broadcast control and as such, exhibits a total lack of robustness to measurement error and therefore it is not a viable proposition. In the end, it is claimed in [2] that the control-sharing information pattern leads to a stochastic control problem that is ill posed and it is stated that "the need for future work on this problem is obvious". Sadly, some bad ideas die hard and this "result" persists in the literature. Unfortunately, and as is clear from the results obtained in this paper, the analysis of LQGDGs with a control-sharing information pattern presented in [1] and [2] is incorrect. In this talk and in Ref. [3] LQGDGs with a control-sharing information pattern are revisited. A careful analysis reveals that although this is a game with partial information and the information pattern is not nested, the control-sharing information pattern makes the game amenable to solution by the method of dynamic programming. Our analysis of dynamic games with a control-sharing information pattern can be extended to account for measurement noise in the transmitted controls, this having the effect of showing up as additional process noise in the system's dynamics. We show that the solution of the "zero-sum" LQGDG with a control-sharing information pattern is similar in structure to the solution of the LQG optimal control problem in so far as the principle of certainty equivalence/decomposition holds: It entails the solution of three Riccati equations and a Lyapunov equation. A Nash equilibrium in delayed commitment strategies is obtained and the solution is time consistent/sub-game perfect. The correct closed-form solution of

LQGDGs with a control-sharing information pattern is obtained. This is a rare instance of a solution of a stochastic dynamic game where the players have partial information.

Dr. Meir Pachter, AFIT

References

[1] Aoki: On Decentralized Linear Stochastic Control, IEEE-AC, 1973.
[2] Sandell & Athans: Solution of Some Non-classical LQG Stochastic Decision Problems, IEEE-AC, 1974.
[3] Pachter: LQG Dynamic Games with a Control-Sharing Information Pattern, Dynamic Games And Applications (DGAA), published online February 17, 2016; to appear in print.

Title: Virtual Service Topology-based Networked Control Techniques for Contested Cognit

Abstract: A virtual service is a concept motivated by component based control whereby a typically hardwired and dedicated service, such as a weapon seeker, is created virtually out of a network of shared sensors, hardware, software functions, and control functions. Virtual services might exist on a single platform or across a network of heterogeneous platforms and allow for the increased utilization of devices and computing while allowing the service to be more robust to failures and more affordable. A number of complexities arise when developing and using virtual services; particularly in control of real-time systems over mobile ad-hoc networks. It will be shown that many aspects of virtual services resemble social networks and several results in network "influence" including new concept of centrality and "betweeness" will be introduced. Diffusion process theory also plays a key role in virtual service control and new results in risk managed control for service contracts.

Dr. Robert Murphey, AFRL/RW

Title: Coverage-Based Human-Swarm Interactions

Abstract: As the number of agents in a network increases, leader-based interaction modalities are no longer viable, where a human operator engages with the team through dedicated leaders. Instead, team-based interaction modalities must be developed. In this talk, we develop a distributed coverage control algorithm for time varying algorithms, and subsequently let the human operator manipulate the density functions as a way of engaging with the team.

Dr. Magnus Egerstedt, Georgia Institute of Technology

Title: Pursuit-Evasion Games in Uncertain Environments

Abstract: We investigate pursuit-evasion problems, between two or more agents, especially when uncertainty and environmental disturbances (e.g., winds or sea currents) are present. Depending on the knowledge available to the players, such pursuit-evasion games often lead to games of limited or asymmetric information. We first consider relay pursuit-evasion problems with two pursuers and one evader and we reduce the problem to a one-pursuer/ one-evader problem subject to a state constraint. In the process, we provide a solution to a problem that seems to have been missed in the extensive differential game literature. Specifically, we provide a complete solution to the “reverse” problem of the

classical homicidal chauffer game, which we call the "suicidal pedestrian." It is shown that the case of point-capture reduces to a special version of Zermelo's Navigation Problem (ZNP) for the pursuer. We then address differential games of pursuit and evasion between two or more players in the presence of an external flow field (e.g., winds or currents). We characterize the regions of initial conditions that lead to capture, as well as the regions that result in evasion when the two players act optimally. For simple fields, Voronoi-like partitions yield a series of decentralized many-to-one pursuit-evasion games. For more realistic flows, we propose a numerical solution by adopting a reachability-based approach. We give conditions for the game to be terminated in terms of reachable set inclusions. Finally, we consider pursuit-evasion games in a stochastic setting. First, a stochastic game theoretic Differential Dynamic Programming (SGT-DDP) algorithm is derived to solve a differential game under stochastic dynamics. We present the update law for the minimizing and maximizing controls for both players and provide a set of backward differential equations for the second order value function approximation. We also develop a sampling-based algorithm designed to solve game-theoretic control problems and risk-sensitive stochastic optimal control problems in terms of forward and backward stochastic differential equations (FBSDEs). By means of a nonlinear version of the Feynman-Kac lemma, we obtain a probabilistic representation of the solution to the nonlinear Hamilton-Jacobi- Isaacs equation, expressed in the form of a decoupled system of FBSDEs. Current work deals with developing a general theoretical framework for solving pursuit-evasion problems with environmental uncertainties. We cast that problem in terms of competitive Markov Decision Processes (MDPs) under the assumption that the two players involved in the game have different opinions on the transition probabilities that govern the dynamics of the system.

Dr. Panos Tsiotras, Georgia Institute of Technology

Day 2 (Aug 3rd 2016):

Title: Hypersonic Vehicle Flight Control

Abstract: The Air Force's interest in hypersonic flight as an enabling technology has been well documented, most recently as described in Air Force Future Operating Concept: A View of the Air Force in 2035. From the perspective of the flight control engineer, both air-breathing and hypersonic glide vehicles pose unique control challenges. This is in part due to the expectation that these vehicles will have significantly more parametric uncertainty as compared to current Air Force operational systems. In the case of scramjet-powered hypersonic vehicles, these vehicles pose additional control issues because their flight dynamics are dictated by a coupling of the aerodynamic and scramjet propulsive forces and moments. Additionally, the test and evaluation infrastructure are unable to support integrated aero-propulsive testing of medium and large scale scramjet-powered vehicles. Because comprehensive ground test data cannot be obtained prior to the flight test program, scramjet-powered vehicles will have higher levels of uncertainty in the aerodynamic and propulsive forces and moments when compared to current USAF systems. This has provided motivation for addressing open problems in adaptive control theory in order to advance and mature the technology to reduce an inherent risk in hypersonic systems. Additionally, other future Air Force systems will likely benefit from such technology as aircraft design paradigms shift for both tactical and strategic aircraft, as well as those future systems that will be entirely autonomous. The research for the past year has focused on a core set of open basic research problems that includes the enforcement of state limits within an adaptive dynamic inversion control framework, the development of a design procedure for an output feedback model reference adaptive control law, and a design approach for sequential loop closure with a model reference adaptive control law.

Michael A. Bolender, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH 45433

Title: Control, Filtering and System Identification for Directed Energy Systems

Abstract: Digital holography has received recent attention for many imaging and sensing applications, including imaging through turbulent and turbid media, adaptive optics, three-dimensional projective display technology and optical tweezing. A significant obstacle for digital holography in real-time applications such wavefront sensing for high energy laser systems and high-speed imaging for target tracking is the fact that digital holography is computationally intensive; it requires iterative virtual wavefront propagation and hill climbing to optimize sharpness criteria. Current research at UCLA is developing real-time methods for digital holography based on UCLA's methods for optimal and adaptive identification, prediction and control of optical wavefronts. The new methods for predictive dynamic digital holography integrate minimum-variance wavefront prediction into digital holography schemes to short-circuit the computationally intensive algorithms for iterative propagation of virtual wavefronts and hill climbing for sharpness optimization.

Dr. Steve Gibson Mechanical and Aerospace Engineering University of California, Los Angeles 90095-1597 gibson@ucla.edu (310)-825-9362

Title: Detection of a Moving Gas Source and Estimation of its Concentration Field with a Sensing Aerial Vehicle

Abstract: The objective of this integrative research effort is to derive guidance laws for a concentration sensor on board a UAV in order to improve the estimation of a concentration field, and to use grid adaptation as a means of low order modelling. The guidance of the sensor is coupled to the performance of the state estimator associated with the reconstruction of a plume resulting from a moving gas source releasing material into the atmosphere. Using a Lyapunov functional to derive the desired trajectory of the UAV, the sensing aerial vehicle is repositioned to spatial regions with more useful information for the concentration estimator. In turn the UAV position dictates the grid adaptation resulting in a reduced order model for the estimator.

The plume is modeled by the diffusion advection equation in a 3-D domain with altitude-varying winds and eddy diffusivities. The UAV dynamics is described using the point-mass model of a fixed-wing aircraft, resulting in a sixth-order nonlinear dynamical system. Through the appropriate choice of a Lyapunov function for the resulting state-estimation error, the estimation scheme provides the desired velocities of the UAV. A lower-level controller in turn accepts these desired velocities as reference inputs and provides the control signals to the UAV in order to follow the desired velocities. A finite volume discretization is employed for the estimator and it incorporates a second-order total variation-diminishing scheme for the advection term. The resulting finite volume-total variation diminishing (FV-TVD) scheme, provides the plume concentration free of oscillations in regions of large gradients. To achieve greater computational efficiency, the dynamic grid adaptation is implemented for the estimator, with local grid-refinement centered at the UAV location. The continuous grid adaptation results in a time-varying state matrix of the finite dimensional representation of the state observer.

Dr. Michael A. Demetriou and Dr. Nikolaos A. Gatsonis, Worcester Polytechnical Institute

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Title: Stochastic dynamical modeling: structured matrix completion of partially available statistics

Abstract: State statistics of linear systems satisfy certain structural constraints that arise from the underlying dynamics and the directionality of input disturbances. In this talk, we study the problem of completing partially known state statistics. Our aim is to develop tools that can be used in the context of control-oriented modeling of large-scale dynamical systems. For the type of applications we have in mind, the dynamical interaction between state variables is known while the directionality and dynamics of input excitation is often uncertain. Thus, the goal of the mathematical problem that we formulate is to identify the dynamics and directionality of input excitation in order to explain and complete observed sample statistics. More specifically, we seek to explain correlation data with the least number of possible input disturbance channels. We formulate this inverse problem as rank minimization, and for its solution, we employ a convex relaxation based on the nuclear norm. The resulting optimization problem is cast as a semidefinite program and can be solved efficiently using general-purpose solvers for small- and medium-size problems. For large-scale systems, we develop a customized alternating minimization algorithm (AMA). We interpret AMA as a proximal gradient for the dual problem and prove sub-linear convergence for the algorithm with fixed step-size. We conclude with an example from fluid dynamics that illustrates the utility of our modeling and optimization framework.

Dr. Mihailo Jovanovic, University of Minnesota

Title: Investigation of the Role of First Principles Physics, Control, and Optimization in Precision Airdrop

Abstract: Physics-based models for all phases of airdrop have been derived that can be used in conjunction with near real-time wind measurements to optimize the air release point for multi-package bundles that are dropped using ballistic drogues and parachutes. The objective of the detailed models is to reduce the effects of modeling error on the accuracy of optimized release points for high-altitude low-opening airdrops. Even though the packages, drogues, and parachutes are not actively controlled, several methods have been developed that can improve precision and accuracy of airdrop. By varying the altitude at which each package transitions from a drogue to a main parachute, a single use control event that leverages the existing ballistic airdrop hardware is introduced. This control event enables the impact location of each package to be placed anywhere on a one dimensional finite length curve on the ground. The exact shape of this curve is determined by the local wind field and the aerodynamic characteristics of each parachute. Optimized timing of the transition event has shown that significant improvements in accuracy and precision can be achieved. For a given 3D wind field, the effectiveness of the one-time control event can be maximized by the selection of an optimal aircraft heading angle, a release point for a given approach altitude, and by ensuring the packages have uniform wind drift coefficients. Deterministic planning algorithms have been developed for optimizing these degrees of freedom for any given airdrop scenario. We obtained an approximate analytical solution to the differential equations that govern the flight of an aerodynamically decelerated package through a wind field. From the differential equation solutions, we derived an analytical solution to the problem of optimizing the transition altitude in order to minimize impact error. Incorporation of the analytical results into a solution algorithm resulted in a 5000x increase in speed when compared to a purely numerical solution; furthermore, the method guarantees a global optimal solution in deterministic time. Implementation on embedded hardware demonstrated that it is feasible to install and run the algorithm on individual packages during descent. By optimizing the drogue-to-main transition altitudes in real-time on the packages themselves, it is possible to continuously re-compute the optimal transition altitude throughout a descent in order to compensate for differences between the a priori estimate of the wind field and the actual wind field encountered by the package, thereby improving accuracy. Additional work has been performed to transition the deterministic planning algorithms into a stochastic framework. This is achieved by backpropagation of a desired ground impact dispersion pattern through altitude by using stochastic Liouville equations. During backpropagation, the desired ground impact dispersion is morphed by the uncertain wind field and uncertain non-linear dynamics of the packages. This morphed distribution can then be used to optimize the aircraft heading

angle, release point, and the drogue-to-main chute transition points. This framework also enables airdrop mission planning to account for complex ground terrain, restricted zones, and provides the ability to shape impact distributions in order to concentrate packages near road networks. The approach is less expensive to implement than a continuously guided parafoil and more flexible and accurate than conventional ballistic airdrop procedures.

Dr. David B. Doman,
AFRL RQQA, 2210 Eighth Street, Suite 21, WPAFB, OH 45433-7531

Title: Surviving the Data Deluge: A Combined Dynamical Systems/Machine Learning Approach

Abstract: Flexible, provably correct autonomy is a key enabler for maintaining the superiority and expanding the capabilities of the USAF in the next two decades. Autonomous systems endowed with analysis and decision capabilities can collect data, assess intention, and if necessary, take action, while at the same time substantially reducing the required manpower and cost, vis-à-vis existing unmanned vehicles. In addition, these systems can prevent crime, give early warning of serious medical conditions, for instance by detecting minute gait alterations preceding a stroke, inspect aging civil infrastructures, and monitor and even coordinate responses to environmental threats to minimize their effect. Arguably, a major road-block to realizing this vision stems from the curse of dimensionality. To successfully operate in these scenarios, autonomous systems will need to timely extract relevant information from very large, multimodal data streams. However, existing techniques are ill-equipped to deal with this “data avalanche”.

Drs. M. Sznaier and O. Camps, Electrical and Computer Engineering Department, Northeastern University, Boston, MA 02115

Title: Stochastic Surveillance via Markov Chain Modeling and Optimization

Abstract: We propose the design of efficient surveillance, information gathering, and coordination strategies for robotic networks in dynamic environments and their application to DOD scenarios. We argue that sensor scheduling, motion planning and coordination algorithms for surveillance and anomaly detection is a crucial objective. The key technological challenge is how to search an area in a persistent manner, with minimal average time to detection, with unpredictable trajectories and with optimally-partitioned workload among multiple assets. The key scientific subject is the study of optimization criteria, convexity properties, relaxations and coordination strategies defined via the theory of Markov chains and random walks. Our technical approach is based on a combination of tools from the study of Markov chains, convex optimization, dynamical systems, distributed algorithms, robotic coordination, and network systems.

PI: Dr. Francesco Bullo, Mechanical Engineering, UC Santa Barbara
Coworkers: Rush Patel, Pushkarini Agharkar, Mishel George, Andrea Carron

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Title: Stochastic Hybrid Systems and Distributed Learning in Asynchronous Networks of Sampled-Data Systems

Abstract: In this talk, we present a general class of stochastic hybrid systems and consider an application to distributed learning in asynchronous networks. The general class of stochastic hybrid systems allows randomness to influence the jumps of the hybrid system and does not insist on unique solutions. The application considers a strongly connected network of asynchronous, sampled-data agents who work to synchronize their actions and probe their (quadratic) steady-state payoff functions stochastically to approach Nash equilibrium. Non uniqueness manifests itself through multiple avenues:

the dynamics that generate the steady-state payoff functions may have non-unique solutions (though a unique steady-state response), and agents are free to choose when they participate in the learning algorithm and when they do not participate.

Dr. Andy Teel, University of California Santa Barbara

Title: Stochastic Control, Networks, Fundamental Solutions and Computational Complexity

Abstract: The discussion will focus mainly on three directions within the larger set under investigation.

The classical approach to solution of conservative dynamical systems is integration of Newton's second law. An alternate viewpoint is that a system evolves along a path that makes the action functional stationary, i.e., such that the first-order differential around the path is the zero element. We show that the stationary-action formulation can be used to generate fundamental solutions to two-point boundary-value problems (TPBVPs) for conservative dynamical systems. Here, a fundamental solution is an object such that one can solve TPBVPs for varying initial and terminal data without the need for re-integration of dynamics and shooting etc. In the case of orbital-mechanics applications, we are addressing both the n-body problem (as a well-known benchmark problem class), and the more practical problem of a single small body moving among a set of large bodies on known trajectories. This last problem pertains not only to trajectory design for man-made vehicles, but to estimation of potential Earth-impacts of comets and asteroids. These questions are also leading to the development of a new foundational area for control theory. In particular, we define the problem class wherein one seeks a stationary point of a payoff, rather than a minimum or maximum. This, in turn, leads to the definition of a ``staticization'' operator, and the development of a theory of dynamic programming for solution of problems in stationarity.

Focusing on optimal resource allocation under a reliability requirement, we have introduced a new framework for decision-based system identification. Identification complexity and its relations to decision making are investigated for networked systems that share a communication resource. Dynamic resource assignment algorithms are developed, and their convergence properties are established, including strong convergence, almost sure convergence rate, and asymptotic normality.

Addressing the essential features of wireless communication systems and their impact on networked systems, we investigate controllability of linear time-invariant systems under irregular and random sampling, and develop adaptive control algorithms with respect to sampling intervals. Using block erasure channels as the main motivating communication platform, we first establish a sufficient condition on sampling density that ensures controllability of sampled systems, which is necessary for feedback design and adaptation. Under this condition, we have further developed causal adaptive feedback algorithms to accommodate time-varying sampling intervals. Implementation of such algorithms encounters technical challenges because future sampling intervals are uncertain or random. Under deterministic slowly-varying and stochastic infrequent Markovian jumping sampling intervals, overall system stability is established.

Drs. William McEneaney
University of California San Diego
Dr. George Yin and Le Yi Wang
Wayne State University

Title: Explicit Solutions for Some Stochastic Differential Games

Abstract: Some stochastic differential games for linear equations are formulated and explicitly solved for multi-agents with quadratic payoffs or exponential quadratic payoffs. Furthermore some stochastic differential games for nonlinear systems in symmetric spaces are formulated and explicitly solved. The methods to solve these stochastic differential games are direct and do not require solving Hamilton-

Jacobi-Isaacs equations or backward stochastic differential equations. The noise processes for some of these models can be fairly general that include the family of fractional Brownian motions.

Dr. Tyrone E. Duncan and Dr. Bozenna Pasik-Duncan University of Kansas

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Title: Estimation of Distributed Parameters in Permittivity Models of Composite Dielectric Materials Using Reflectance

Abstract: We investigate the feasibility of quantifying properties of a composite dielectric material through the reflectance, where the permittivity is described by the Lorentz model in which an unknown probability measure is placed on the model parameters. We summarize the computational and theoretical framework (the Prohorov Metric Framework) developed by our group in the past two decades for nonparametric estimation of probability measures using a least-squares method, and point out the limitation of the existing computational algorithms for this particular application. We then demonstrate the feasibility of our proposed methods by numerical results obtained for both simulated data and experimental data for inorganic glass when considering the resonance wavenumber as a distributed parameter.

This research represents joint efforts with colleagues at NCSU (Jared Catenacci and Dr. Shuhua Hu) and collaborative research efforts of our group with scientists at AFRL (Materials State Awareness and Supportability Branch, Air Force Research Lab, WPAFB 45433, USA) led by Amanda K. Criner and Adam T. Cooney. In these efforts, the goal is to develop a noninvasive technique to characterize the degradation of a complex nonmagnetic dielectric material (e.g., ceramic matrix composites, which are used in a wide range of applications such as high temperature engines) by assessing the small physical and chemical changes in the material using reflectance spectroscopy. This involves determining the components of the permittivity of the composite dielectric medium using the measured spectral responses.

Dr. H.T. Banks, Center for Research in Scientific Computation North Carolina State University Raleigh, NC 27695-8212 USA

Title: Optimal Mass Transport for Statistical Estimation, Image Analysis, Information Geometry and Control

Abstract: We will describe some of the key issues in visual control and tracking that have been the focus of our AFOSR sponsored research. We have developed a general framework for geometric observer-like structures based on non-parametric implicit (level set) curve descriptions of dynamically varying shapes. We have considered the geometric nature of the dynamical system as well as the key issue of robustness. As it turns out, the concept of robustness in this framework is strongly connected to ideas from optimal mass transport theory that also allow us to define new measures on the shape manifold characterized via certain probability distributions. Finally, we will sketch some practical methods (based on optimal control) for numerically solving the optimal transport (Monge-Kantorovich) problem.

Dr. Tryphon T. Georgiou, University of Minnesota and Dr. Allen R. Tannenbaum, Stoneybrook University

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Title: Synthesis of Reduced-Order Modeling, Global Sensitivity Analysis, and Uncertainty Quantification for Robust Control Design of Nonlinear Smart Composite Systems

Abstract: In this presentation, we will discuss the role of global sensitivity analysis, reduced-order model development, and uncertainty quantification to improve robust control designs for AFOSR applications utilizing advanced transductive materials. To motivate this analysis, we consider piezoelectric materials employed for improved flow control and drive mechanisms for micro-air vehicles such as Robobee. We

will summarize the development of physics-based nonlinear models and the construction of reduced-order models, which are appropriate for design and control implementation, via dynamic mode decompositions. We will also discuss the use of global sensitivity analysis and active subspace techniques to isolate those inputs that can be calibrated using measured responses. Finally, we will discuss the manner in which subsequent Bayesian model calibration and uncertainty propagation can be used to improve robust control designs.

Dr. Ralph C. Smith, North Carolina State University

Day 3 (Aug 4th 2016):

Title: Numerical Analysis of Distributed Optimal Control Problems Governed by Elliptic Variational Equalities (or Inequalities of an Obstacle Type) with a Parameter

Abstract: The convergence of a family of continuous distributed mixed optimal control problems (*Pa*), governed by elliptic variational equalities, when the parameter *a* (the heat transfer coefficient) goes to infinity was studied in Gariboldi - Tarzia, Appl. Math. Optim., 47 (2003), 213-230 and it has been proved that it is convergent to a distributed mixed elliptic optimal control problem (*P*). We consider the discrete approximations (*Pha*) and (*Ph*) of the optimal control problems (*Pa*) and (*P*) respectively, for each positive numbers *h* and *a*. We study the convergence of the discrete distributed optimal control problems (*Pha*) and (*Ph*) when *h* goes to zero, *a* goes to infinity and (*h,a*) goes to (zero, infinity) obtaining a complete commutative diagram, including the diagonal convergence, which relates two continuous and two discrete distributed mixed elliptic optimal control problems (*Pha*), (*Pa*), (*Ph*) and (*P*) by taking the corresponding limits. The convergent corresponds to the optimal control, and the system and adjoint system states in adequate functional spaces.

A similar complete commutative diagram can be obtained among two continuous (Boukrouche-Tarzia, Comput. Optim. Appl., 53 (2012), 375-393) and two discrete distributed mixed optimal control problems when the system states are governed by elliptic variational inequalities of an obstacle type with a positive parameter *a*.

Dr. Domingo Alberto Tarzia, CONICET - Depto. Matemática, FCE, Univ. Austral, Paraguay 1950, S2000FZF Rosario, Argentina.

Title: Mean Field Games and the Control of Large Scale Systems

Abstract: Mean Field Game (MFG) theory provides tractable strategies for the decentralized control of large scale systems. The power of the formulation arises from the relative tractability of its infinite population McKean-Vlasov (MV) Hamilton-Jacobi-Bellman equations and the associated MV-Fokker-Planck-Kolmogorov equations, where these are linked by the distribution of the state of a generic agent, otherwise known as the system's mean field. The resulting decentralized feedback controls yield approximate Nash equilibria and depend only upon an agent's state and the mean field.

Applications of MFG theory are being investigated within engineering, finance, economics and social dynamics, while theoretical developments include existence and uniqueness theory for solutions to the MFG equations, major-minor (MM) agent systems containing asymptotically non-negligible agents, non-

linear estimation theory for MM-MFG systems, and the comparison of centralized (optimal) control and MFG control performance. In this talk we shall review recent advances in the last two topics.

Peter E. Caines
McGill University, Montreal

Title: Compressive Feedback Control Design for Spatially Distributed Systems

Abstract: A sparse linear dynamical network is one whose number of interconnection links is proportional to its number of subsystems.

Optimal design problems for sparse networks are more amenable to efficient optimization algorithms. More importantly, maintaining such networks are usually more cost effective due to their reduced communication requirements. Therefore, approximating a given dense network by a suitable sparse network is an important analysis and synthesis problem. In this presentation, I report our progress on development of a framework to produce a sparse approximation of a given large-scale network with guaranteed performance bounds using a nearly-linear time algorithm, i.e., with complexity of O(n logn). The main focus of this presentation is on the class of linear consensus networks.

Dr. Nader Motee, Lehigh University

Title: BRI-Theory-based Engineering of Biomolecular Circuits in Living Cells

Abstract: The objective of this research is to establish a data-driven theoretical framework based on mathematics to enable the robust design of interacting bimolecular circuits in living cells that perform complex decision-making. Microbiology as a platform has substantial advantages with respect to human-made hardware, including size, power, and high sensitivity/selectivity. While the latest advances in synthetic biology have rendered the creation of simple functional circuits in microbes possible, our ability of composing circuits that behave as expected is still missing. This hinders the possibility of designing robust complex decision-making circuits, including recognition and classification of chemical signatures. Overcoming this bottleneck goes beyond the engineering of new parts or new assembly methods. By contrast, it requires a deep understanding of the dynamical interactions among synthetic modules and the cell machinery, a particularly hard task since dynamics are nonlinear, stochastic, and involve multiple scales of resolution both in time and space. In this project, we propose an interdisciplinary approach merging mathematics, control and dynamical systems theory, electrical circuit theory, and synthetic biology, in order to tackle this problem. We propose to establish a design-oriented theoretical framework that explicitly accounts for interactions among circuits, between the circuits and the cell machinery, and provides engineering solutions to mitigate the undesirable effects of these interactions (compositionality effort). Within this framework, we will develop mathematical tools to quantify the propagation of stochasticity through the nonlinear dynamics of biological networks (stochasticity effort) and to incorporate spatial heterogeneity effects (spatial heterogeneity effort). These research efforts will be focused on solving concrete engineering problems on prototype experimental systems that integrate different sensors to classify a number of chemical signatures.

PI: Drs. Del Vecchio D. (MIT) co-PIs: Collins J. J., Murray R. M., Sontag E. D

Title: DSOS and SDSOS Techniques in Optimization and Control

Abstract: "DSOS and SDSOS optimization" techniques are more scalable alternatives to sum of squares (SOS) optimization which instead of semidefinite programming rely on linear and second order cone programming. They have been successfully used (for example) to find a stabilizing controller for a model of a humanoid robot with 30 state variables, and can handle quartic polynomial optimization problems

with 50-70 variables in the order of a few minutes. In this talk, we review the theoretical and numerical aspects of these algorithms and present new directions for improving their approximation quality in an iterative fashion.

Based on joint work with Anirudha Majumdar.

Dr. Amir Ali Ahmadi, Princeton, ORFE

Title: Idempotent methods for worst-case analysis and optimal control

Abstract: Worst-case analysis and optimal control problems concern the evaluation and design of dynamical system behavior with respect to a specific performance measure, cost, or payoff. They are readily posed via the definition of a suitable value function as the infimum or supremum of this performance measure over a set of inputs, subject to constraints imposed by the underlying system dynamics. A value function is typically identifiable with the unique solution of a Hamilton-Jacobi-Bellman (HJB) partial differential equation (PDE), thereby providing an in-principle path for its computation via standard verification arguments. A state feedback characterization for the worst-case or optimal input typically follows from such a computation, thereby providing a robust solution to the problem of interest.

HJB PDEs are very difficult to solve in practice. Explicit solutions are exceedingly rare, and computational methods are typically required for their approximation. Methods based on discretization of the state and/or input spaces do not scale well with problem dimension, leading to intractability for all but modest problem dimensions. This *curse-of-dimensionality* routinely limits the applicability of worst-case analysis and optimal control theory.

Idempotent methods provide a promising alternative solution path for worst-case analysis and optimal control problems. They target the dynamic programming principle directly, rather than\ the HJB PDE that follows from its incremental limit. Idempotent methods are founded on three desirable algebraic properties of the dynamic programming evolution operator, namely, (i) linearity with respect to a suitable idempotent algebra, (ii) a semigroup property inherited from dynamic programming, and (iii) its preservation of semi-convexity. These three properties have been shown to give rise to two explicit fundamental solution semigroups of integral operators that underpin the evolution of dynamic programming evolution operators from the identity, with respect to time horizon. Approximations of the associated operator kernels naturally give rise to so-called eigenvector methods, while structural invariance (where available) has yielded curse-of-dimensionality free methods for specific problem classes.

This presentation will motivate the notion of idempotent fundamental solution semigroups that attend worst-case analysis and optimal control problems, and highlight their application in the development of idempotent methods. A novel construction of a solution group for a class of wave equations, encapsulated within a worst-case analysis problem via the principle of stationary action, will provide an unconventional illustration of this application.

Dr. Peter M. Dower, University of Melbourne

Title: Optimal Sensor Location in Distributed Parameter Systems

Abstract: For control systems that are distributed in space, such as vibrations and chemical diffusion, the locations and design of the control hardware, the actuators and sensors, are important design variables. In particular, optimal locations of actuators and sensors are often different from locations chosen based on physical intuition. Prior analysis on placing control hardware in optimal locations is crucial, since it is often too difficult move hardware once it is placed. A mechatronic approach, where the controller design is integrated with actuator location, has been followed by my group in recent work on optimal actuator location. Fundamental statements about the well-posedness of various actuator location problems and also conditions under which approximations provide correct results. The focus of the present proposal is optimal sensor location. Most, but not all, of the theoretical questions follow from optimal actuator location. Most importantly, this aspect of the research has a number of important applications; including estimation of state in structures and thermostat placement to improve building efficiency. A number of questions can be addressed as a consequence of results in optimal sensor location. One question involves sensor selection: for a given expenditure, which choice yields better performance, a small number of high quality sensors or a larger number of inexpensive sensors?

Dr. Kirsten Morris, University of Waterloo

Title: Analysis of Spatially Extended Dynamical Systems with Applications to Agent-Based Models

Abstract: The objective of our research is to develop methods that can help analysis and control of social-cyber-physical systems, with interactions that can include spatially distributed, discrete and stochastic effects. In this context, the method of the Koopman Mode Analysis was developed for spatially extended systems with deterministic and stochastic interactions. We apply the methodology to two examples of agent-based models and study how preferential gathering sites and small world network structure affect coarse-grained dynamics. We also apply the Koopman Mode Analysis to the problem of fluid flow around a cylinder in an oscillating flow that mimics the behavior of flow configurations that exhibit dynamic stall, uncovering a novel attractor structure that we call the Quasi-Periodic Intermittency. We also present a theory that exhibits the connection between the Koopman Mode Decomposition, resolvent mode decomposition, and invariant solutions of the Navier-Stokes equations, organizing a variety of approaches to spatially extended systems into a uniform framework. Finally, we present the use of the Koopman operator theory tools to the problem of achieving the given coverage density on a terrain by the use of multiple mobile agents.

Dr. Igor Mezic, University of California, Santa Barbara

Title: Fragility of Networked Systems

Abstract: The emergence of large networked systems has brought in new challenges to researchers and practitioners alike. While such systems perform well under normal operations, they can exhibit *fragility* in response to certain disruptions that may lead to catastrophic cascades of failures. This phenomenon, referred to as *systemic risk*, emphasizes the role of the system interconnection in causing such, possibly rare, events. The flash crash of 2010, the financial crisis of 2008, the New England power outage of 2003, or simply the large delays in air travel are just a few of many examples of fragility and systemic risk present in complex interconnected systems.

Robust interconnections have been the subject of study by the control community for several decades. Substantial progress has been made in the context of both stability and performance robustness for various types of interconnections. Typical problems addressed in the literature involved interconnections with simple topologies but with more complex components (dynamic, sometimes with high dimensions).

More recently, the attention of the research community shifted towards networked systems where the topology of the network is fairly large and complicated while the local dynamics are fairly simple. The term fragility is used in this context to highlight the system's closeness to failure. Notions of failure include large amplification of local disturbances (or shocks), instability, or a substantial increase in the probability of extreme events. Cascaded failures or systemic risk fit under this umbrella and focuses on local failures synchronizing to cause a break down in the network. Many abstracted models from transportation, finance, or the power grid fit this framework well. The focus of research is to relate fragility to the size and characteristics of a network for certain types of local interactions.

In this talk, I will address this emerging area. I will give some constructive examples and highlight important research directions.

Dr. Munther Dahleh, MIT

Title: State-dependent Dynamic Networks: Reachability, Regularity, and Quasi-Randomness

Abstract: In this talk I will discuss the notion of state dependency in dynamic networks, where network properties are influenced by the state of a dynamic system that can potentially be controlled. An example of such network properties include the existence of an edge as a function of the states of incident nodes as well as adaptive edge weights that are updated as a function of node states. In this direction, we explore distributed equation solving on graphs as a subroutine in the adaption mechanism and how its convergence affects the performance of the adaptation mechanism.
If time permits, we then explore connections between state-dependent networks and random graphs through the notion of regularity as well as the role of time scales in analyzing state-dependent networks.

Dr. Mehran Mesbahi,
University of Washington

Title: Optimal Realizable Networked Controllers for Networked Systems.

Abstract: Our main objective is to systematically design networked controllers for networked systems. The controllers should achieve optimal networked performance criteria, and should be provided with a networked realization, i.e., in terms of subsystems interacting over the existing communication network in a distributed fashion. We plan to apply the design methodology to improve the performance of networked systems and distributed computing systems. Our approach is centered on the development of a system theory for networked systems.

We introduce the notions of network implementability and network realizability and analyze the structure of network implementable and realizable systems. Based on the definition and characterization of network realizable systems, we propose the derivation of systematic optimal networked distributed controllers with networked realizations.

Dr. Nicola Elia Dept. of Electrical Engineering Iowa State University

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Title: Reconfigurable Algorithms for High Performance and Robust Autonomy in Complex Networks

Abstract: The rapid growth of digital networks has enabled systems at different locations to perform joint tasks, such as coordination, synchronization, and estimation. At the same time, it has brought about analysis and design challenges, mainly due to the presence of events, heterogeneity, distributed information, as well as unavoidable uncertainty in the models and data. In this talk, I will present recently developed tools for the design of decentralized observers and controllers that not only confer high performance and robustness, but also efficiently handle the presence of continuous and discrete behavior in complex networks. The algorithms obtained from these new methods combine hybrid estimation strategies with hybrid control strategies for synchronization of multi-agent systems so as to reconfigure and control the agents.

Dr. Ricardo Sanfelice, UCSC
