Interdisciplinary Studies in Intelligent Systems
Department of Electrical Engineering
University of Notre Dame

The 2nd Midwest Workshop on Control and Game Theory (WCGT–2013)

April 26-27, 2013

Technical Report of the ISIS Group
at the University of Notre Dame
ISIS-2013-003
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Organized by

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Overview

The 2nd Midwest Workshop on Control and Game Theory (WCGT-2013) brought together over 60 active researchers, students and faculty members from the midwest region of the United States (University of Notre Dame, University of Illinois at Urbana-Champaign, Purdue University, the Ohio State University, University of Denver and Corvinus University of Budapest, Hungary), who have developed and applied game and control theory to analyze, design and assess complex systems. A special focus of this workshop was to provide a forum and highlight synergies between various related research areas, encourage discussions and facilitate collaborations on new game and control theoretic methodologies.

The workshop topics included:

- Dynamic games and applications; Stochastic games; Learning and adaptive games; Evolutionary games; Cooperative games; Theory of optimal control and dynamic games; Stochastic optimization theory; Optimal and robust control designs; Adaptive and nonlinear control theory; Hybrid and switched systems; Real-time control problems; Control of multi-agent systems; Networked control systems; Control over networks; Control of energy systems; Large scale optimization problems; Quantification of uncertainty.
- Applications: telecommunications, transportation, smart grids, security, energy and resource management, economic dynamics, finance, management, environment, epidemiology, social sciences, system biology.

The program comprised twenty five stimulating presentations, twelve of which were invited presentations. Each invited presentation had a length of twenty five minutes with at least five minutes discussion time, with one invited presentation of length fifty minutes. The remaining presentations were fifteen minutes long.

The presentations were organized into sessions on the topics:

- Stochastic Optimization and Game Theory (Four Invited Presentations)
- Nonlinear Dynamics and Systems Theory (Two Invited Presentation)
- Large-Scale Distributed Systems (Three Invited Presentations)
- Hybrid and Switched Systems (Three Invited Presentations)
- Students Sessions (Three Sessions, Thirteen Presentations)

In addition to the scientific program, graduate students from Notre Dame organized a campus tour on Saturday afternoon. The campus tour also comprised of a research laboratory visit at the Department of Electrical Engineering, University of Notre Dame. Finally, it was decided that the next year's workshop (WCGT-2014) will take place at the Ohio State University.

Based on the feedback from the participants, the workshop was very successful in meeting its objectives.

Financial and logistic support for the workshop was provided by the College of Engineering and the Department of Electrical Engineering, University of Notre Dame, and it is gratefully acknowledged.

Abstracts

Title: **Stochastic Differential Games and Intricacy of Information Structures**

Author: **Tamer Başar** (University of Illinois at Urbana-Champaign, basar1@illinois.edu)

Coauthor(s): -

Abstract: In spite of decades long past research activity on stochastic differential games, there still remain some outstanding fundamental questions on existence, uniqueness, and characterization of non-cooperative equilibria when players have access to noisy state information. This talk will identify these questions, along with the underlying challenges, and address a number of them within specific contexts by focusing on two-player zero-sum stochastic differential games (ZSSDGs). One specific class the talk will dwell on is games where the state information is acquired by the players through an intermittently failing noisy channel, where the failure is governed by a time-independent Bernoulli process. When the failure rate is zero, this corresponds to the standard ZSSDG with identical noisy measurements for the players (in which case derivation of the "complete" saddle-point solution is still quite subtle, as will be discussed in the talk). For the other extreme case when the failure rate is one, we have the open-loop ZSSDG. For the intermediate case, the saddle-point solution involves, under some conditions, a Kalman filter (or an extended Kalman filter) with intermittent (or missing) measurements; in this case, a restricted certainty equivalence holds. A variant of this is the more challenging class of problems where the failure of the transmission of the common noisy measurement of the state to the players is governed by two independent Bernoulli processes with possibly different rates. This class of ZSSDGs, which will be discussed briefly, involves two scenarios: (i) the players are not aware of the failure of links corresponding to each other, and (ii) this information is available (that is players share explicitly or implicitly the failure information) but with one step delay. Extensions to (i) multi-player ZSSDGs (with teams playing against teams, where agents in each team do not have identical information), and (ii) nonzero-sum stochastic differential games (with asymmetric information among the players) constitute yet two other classes of challenging problems, which will be touched upon toward the end of the talk.

Title: **Formulating and Solving Portfolio Decision and Asset Pricing Problems**

Author: **Thomas Cosimano** (University of Notre Dame, tcosiman@nd.edu)

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Abstract: The investors optimal portfolio problem is analyzed when the investor has stochastic differential utility over terminal wealth and intermediate consumption. The investor assumes that the expected returns on US government bonds follow the affine term structure model of Josilin, Singleton and Zhu (2011). The expected return on stocks and inflation follow a state space model in which aggregate US stock returns, inflation and the price?dividend ratio is observed. Consequently, the expected returns on assets are a function of five factors, which follow an Ohnstein?Uhlenbeck stochastic process as in

Sangvinatsos and Wachter (2005) and Liu (2007). The preferences follow the stochastic differential utility model of Duffie and Epstein (1992), as in Schroder and Skiadas (1995, 2005). Following Wachter (2010) it is well know that the investors problem leads to a nonlinear partial differential equation (PDE) which has a solution that is a function of time to maturity, t, and the five factors, X.

This paper provides a new derivation of the homogenous component of the nonlinear PDE. First, a particular, solution to the homogenous PDE is found $h(t, X) = \exp -\delta t \exp(X^T AX + B^T X)$. $\delta > 0$ is an endogenous discount factor dependent on the parameters of the PDE. A and B are constant matrices which are also dependent on the parameters in the PDE. A is the solution to a Ricatti algebraic equation which is associated with a deterministic infinite horizon linear quadratic (LQ) investment problem. This problem minimizes the variance of the assets over time with respect to the five factors by choosing a control, which impacts the deterministic equation of motion for the risk neutral expected factors. It turns out that the ODEs in Sangvinatsos and Wachter (2005) and Liu (2007) solution procedure applies to the finite horizon version of this LQ problem.

This particular, solution is not the general solution to the original PDE, since a general specification $f(t, X) = g(t, X)h(t, x)$ leads to another PDE. This second PDE is a function of the first and second derivatives of $g(t, X)$. Fourier analysis of this new PDE leads to the general solution $f(t, X)$, which is a also a Gaussian function of the five factors, however the coefficients are dependent on the time horizon of the investor. This solution is well defined when the solution to the deterministic LQ problem is symmetric and positive definite. This condition is needed for the application of the Fourier transform in higher dimensions. Following the known properties of the LQ control problem, conditions on the risk neutral expected return and the effect of the factors on the standard deviation of assets are established, which assures the general solution is well defined. This solution is compared to the solution found by in Sangvinatsos and Wachter (2005) and Liu (2007) for the case of constant relative risk aversion for both terminal wealth optimization, as well as intermediate consumption. The general solution can also be used to solve the stochastic differential utility case, when the investor cares only about terminal wealth by using a nonlinear transformation similar to Cole-Hopf. Finally, the general solution can be used to construct a high order perturbation approximation of the stochastic differential utility case following Bender and Orszag (1999).

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Title: **Optimal Compensation with Earnings Manipulation**

Author: **Thomas Gresik** (University of Notre Dame, tgresik@nd.edu)

Coauthor(s): **Keith Crocker** (Pennsylvania State University)

Abstract: The optimal managerial compensation contract is characterized in an environment in which the manager influences the distribution of earnings through an unobservable effort decision. Actual earnings, when realized, are private information observed only by the manager, who may engage in the costly manipulation of earnings reports. We derive the optimal contract that guarantees the manager non-negative profit for any earnings realization (interim individual rationality) to ensure manager retention. We find that the optimal contract induces under-reporting for low earnings and over-reporting for high earnings, and that the optimal contract may be implemented through a compensation package composed of a performance bonus based upon (manipulated) earnings and a stock option that is repriced to be strictly in the money for intermediate earnings realizations and at the money for low earnings realizations.

Title: **Exclusive Contracts with Product Differentiation in Successive Oligopolies**

Author: **Barna Bakó** (Corvinus University of Budapest, barna.bako@uni-corvinus.hu)

Coauthor(s): -

Abstract: This paper investigates the incentives of manufacturers to deal exclusively with retailers in bilaterally oligopolistic industries with brand differentiation by manufacturers. With highly differentiated products exclusive contracts are shown to generate higher profits for symmetric manufacturers, who thus have an incentive to insist on exclusive contracting. However, if the products are close substitutes no exclusivity will emerge in equilibrium. By introducing asymmetric upstream firms we find that the cost effective manufacturers offer unilaterally exclusive contracts to retailers when product differentiation is moderate.

Title: **Symmetries for Stability and Control of Multi-agent Nonlinear Systems**

Author: **Bill Goodwine** (University of Notre Dame, billgoodwine@nd.edu)

Coauthor(s): -

Abstract: We present recent results exploiting the symmetric structure often present in nonlinear multi-agent engineering systems to derive low-dimensional conditions for stability. Symmetric systems are common in multi-agent engineering systems, the simplest examples of which would be coordinating systems with many identical agents. Stability does not require that each individual agent be stable, but rather depends, naturally, on the interaction of the agents. We define an equivalence class of symmetric systems for which stability is an invariant property. Hence, a controls engineer only has to check the stability of one member of the entire equivalence class in order to guarantee stability of the entire class. We also present recent extensions of these results to approximately symmetric systems. Such systems have a symmetric "core" but allow for deviation from exact symmetry, which is important in real engineering systems where identical agents can not be guaranteed, either due to small variations in manufacture, or intentional variations by design.

Title: **Invited Tutorial: $\mathcal{L}_1$ Adaptive Control and Its Transition to Practice**

Author: **Naira Hovakimyan** (University of Illinois at Urbana-Champaign, nhovakim@illinois.edu)

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Abstract: The history of adaptive control systems dates back to early 50-s, when the aeronautical community was struggling to advance aircraft speeds to higher Mach numbers. In November of 1967, X-15 launched on what was planned to be a routine research flight to evaluate a boost guidance system, but it went into a spin and eventually broke up at 65,000 feet, killing the pilot Michael Adams. It was later found that the onboard adaptive control system was to be blamed for this incident. Exactly thirty years later, fueled by advances in the theory of nonlinear control, Air Force successfully flight tested the unmanned unstable tailless X-36 aircraft with an onboard adaptive flight control system. This was a landmark achievement that dispelled some of the misgivings that had arisen from the X-15 crash in 1967. Since then, numerous flight tests of Joint Direct Attack Munitions (JDAM) weapon retrofitted with adaptive element have met with great success and have proven the benefits of the adaptation in the presence of component failures and aerodynamic uncertainties. However, the major challenge related to stability/robustness assessment of adaptive systems is still being resolved based on testing the closed-loop system for all possible variations of uncertainties in Monte Carlo simulations, the cost of which increases with the growing complexity of the systems. This talk will give an overview of the limitations inherent to the conventional adaptive controllers and will introduce the audience to the L_1 adaptive control theory, the architectures of which have guaranteed robustness in the presence of fast adaptation. Various applications, including flight tests of a subscale commercial jet, will be discussed during the presentation to demonstrate the tools and the concepts. With its key feature of decoupling adaptation from robustness L_1 adaptive control theory has facilitated new developments in the areas of event-driven adaptation and networked control systems. A brief overview of initial results and potential directions will conclude the presentation.

Title: **Dissipative Switched System Theory for Stability of Networked Systems**

Author: **Michael McCourt** (University of Notre Dame, mmccour1@nd.edu)

Coauthor(s): **Panos J. Antsaklis** (University of Notre Dame)

Abstract: This presentation focuses on the problem of maintaining stability when connecting switched systems over a network with delays. The approach taken is based on dissipativity theory and passivity theory for switched systems. The traditional notions of passivity and dissipativity provide results that can be used to show stability for feedback interconnections. However, when interconnected over a delayed network, these results are not guaranteed. This presentation addresses one approach for compensating for delays in a network control systems. An additional issue with using passivity or dissipativity, is that demonstrating that a system meets the property is a non-trivial search for an energy storage function. This issue is addressed by introducing a computational method, based on sum of squares optimization, of determining that a switched system is passive or dissipative.

Title: **An Iterated Best Response Approach to Decentralized Control of Stochastically Switched Systems**

Author: **Anshuman Mishra** (University of Illinois at Urbana-Champaign, `mishra10@illinois.edu`)

Coauthor(s): **Cédric Langbort and Geir E. Dullerud** (University of Illinois at Urbana-Champaign)

Abstract: This work considers an optimal decentralized control problem for a stochastically switched linear system. The corresponding system and cost matrices depend on distributed stochastic parameters which are available to the local player instantaneously, but with a one time step delay to the other. These parameters are assumed to be independent Markov chains whose statistics are known globally.

We approach this problem by first solving the one stage (static) problem using an iterated best response approach, where each player starts with an arbitrary strategy and repeatedly applies the best response mappings of both the players alternatively. We prove that this iteration converges to the optimal strategy. Assuming a one step delayed sharing (quasi-classical) information structure, we extend the one stage result to multiple stages through dynamic programming. Since each player has access to all past measurements and parameters, it can use a centralized Kalman filter to estimate the current state. The optimal strategy obtained was found to be linear in the local measurements and the estimated state, with the corresponding coefficient matrices being functions of local parameters. These coefficient matrices can be obtained through solving a set of linear equations.

Although the static problem here can also be solved using existing results in Team decision theory first introduced by Radner, such an approach can be successfully applied only when the structure of the controller is known or can be guessed. So in order to demonstrate the advantage of the iterated best response approach, we provide an example of a nonlinear static problem where guessing the structure of the solution is generally impossible. This method can be particularly helpful to find approximate strategies through numerically iterating the best responses.

Title: **A Lyapunov-based Small-Gain Theorem for Interconnected Switched Systems**

Author: **Guosong Yang** (University of Illinois at Urbana-Champaign, yang150@illinois.edu)

Coauthor(s): **Daniel Liberzon** (University of Illinois at Urbana-Champaign)

Abstract: The study of interconnected systems plays a significant role in the development of stability theory of dynamic systems, as it allows one to investigate the stability property of a complex system by analyzing its less complicated components. In this context, the small-gain theorems have proved to be important tools in the analysis of feedback connections of two systems, which appear frequently in the control literature. A comprehensive summarization of classical small-gain theorems regarding linear input-output gains can be found in [2]. This technique was then generalized to nonlinear feedback systems in [5] and [13] within the input-output context. The notion of input-to-state stability (ISS) proposed in [17] was naturally adopted and extended in [7] to establish a general small-gain theorem with nonlinear gains to guarantee both external and internal stabilities. Instead of examining the behavior of actual solutions, a Lyapunov-type nonlinear small-gain theorem was then developed in [6] based on the construction of ISS Lyapunov functions. In this paper, we explore the stability property of interconnected switched systems. The study of switched systems has attracted a lot of attention in recent years (see, e.g., [9] and references therein). It is well-known that, in general, a switched system does not necessarily inherit the properties of its subsystems. For example, in [9, Chapter 2] it is shown that a switched system consisting of asymptotically stable subsystems may not be stable. In [4] it has been proved that such a switched system is asymptotically stable if the switching signal satisfies certain average dwell-time conditions. This result was then extended to the ISS context in [18] and the IOSS (input/output-to-state stability) context in [14], both for nonlinear systems. Moreover, in [14] the IOSS property of a switched nonlinear system was examined also for the case where some of the subsystems are not input/output-to-state stable.

In this work, a sufficient condition is formulated to guarantee the global asymptotical stability (GAS) of an interconnected system consisting of two switched systems under the assumption that in both switched systems there may exist some subsystems that are not input-to-state stable (non-ISS). It is proved that, providing the switching signal neither switches too frequently (average dwell-time constraint) nor activates non-ISS subsystems for too long (time-ratio constraint), a small-gain theorem can be established by introducing two fictitious timers and adopting hybrid system techniques. In particular, for each switched system, a hybrid system is defined such that their solutions are correspondent and the constraints on the switching signal are modeled by the fictitious timers. An ISS Lyapunov function for each hybrid system is then constructed to show that the hybrid system, and therefore the switched system, is input-to-state stable. Although this result had already been proved in [14], the Lyapunov-type formulation in this paper exhibits improvement in the sense that it not only generates an ISS Lyapunov function which is used later in the study of the interconnected system, but provides means for robustness analysis as well. With these two ISS Lyapunov functions, a small-gain condition is then established to prove the GAS property of the interconnected system.

Hybrid systems are dynamic systems that possess both continuous-time and discrete-time features. Trajectory-based small-gain theorems for interconnected hybrid systems

were first presented in [15] and [8], while Lyapunov-based formulations were introduced in [10]. The concept of ISS Lyapunov function was extended to hybrid systems in [1]. In our analysis of hybrid systems, we have adopted the modeling framework presented in [3], which proves to be general and natural from the viewpoint of Lyapunov stability theory. In the hybrid system context, a detailed study of small-gain theorems based on the construction of ISS Lyapunov functions using this framework can be found in [16], [11] and [12]. Com- paring to [12], our result is more general since it applies to the situation where the original ISS Lyapunov functions are increasing not only at the jumps but also during some of the flows. Basing on the idea of restricting non-ISS subsystems activation time proportion proposed in [14], an aforementioned fictitious timer is introduced in the construction of the hybrid system to manage the non-ISS flows.

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Title: **Supervisor Synthesis of Uncertain Discrete-event Systems: An L^* learning-based Approach**

Author: **Jin Dai** (University of Notre Dame, `jdai1@nd.edu`)

Coauthor(s): **Hai Lin** (University of Notre Dame)

Abstract: In this talk, we report some progress made on supervisor synthesis for discrete-event systems with incomplete or blank knowledge of the transition dynamics underneath. Our basic idea is to tune the supervisor decision table online based on observing the event strings generated from the plant. Both the control with complete observations and partial observations are Angluin's L^*? learning procedure based online synthesis algorithms are proposed. In the complete observation circumstances, we use queries to an equivalence oracle and a dynamical membership oracle to learn a minimal deterministic finite automaton which is consistent with the supremal controllable sublanguage of the given specification language. The learning-based online synthesis algorithm is further extended to the case of partial observations, and the controllable and normal sublanguage of a given specification language is calculated. The correctness and convergence properties of the algorithms are proved, and their implementation and effectiveness are illustrated through examples.

Title: **Vehicle Routing Problems for Unmanned Air Vehicles and Game Theory Possible Research Areas**

Author: **Cihan Ercan** (University of Illinois at Urbana-Champaign, `cercan@illinois.edu`)

Coauthor(s): **Tamer Başar** (University of Illinois at Urbana-Champaign)

Abstract: The Dynamic Unmanned Aerial Systems Routing Problem (DUASRP) is a variant of the classic Vehicle Routing Problem (VRP) in which both planned and unplanned targets are observed by a heterogeneous fleet of UASs with various range of capacities, endurances or costs. Searching the targets on-line in AOR and updating the routes in real time while minimizing the undesirable route time increases and route changes.

Military operations are conducted in the presence of uncertainty, much of which is due to unpredictable enemy actions. There are many sources of that kind of randomness in both military and civilian affairs, all of which we attribute here to choices by Mother Nature, a fictional decision maker who makes choices unpredictably, but never with any regard for their consequences. Uncertainty about enemy action deserves a different

kind of treatment, since an enemy by definition has strong feelings about the combat outcome. Decision making against an enemy differs qualitatively from decision making against Mother Nature. Analysts have followed two separate lines of thought in trying to deal with multi-sided decision-making situations. One line of thought is theoretical and leads to game theory. The other is experimental and leads to war gaming.

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Title: **Eco-Drive Velocity Profile Generation for Minimum Fuel Consumption Using Cloud Computing**

Author: **Engin Ozatay** (Ohio State University, ozatay.1@osu.edu)

Abstract: In this study a new framework for energy consumption minimization of conventional vehicles by means of velocity profile optimization for given source and destination points is proposed. A regional network information has been stored in the memory of remote computing unit referred as Cloud. Upon receiving the desired trip information from a driver the cloud generates a route. The stop signs, GIS information and the velocity limits on the route are incorporated into the optimization problem as constraints. Initially, the problem is solved using spatial domain dynamic programming (DP) in the cloud. Next, utilizing the traffic light operation information, a new optimization problem has been generated ensuring the arrival to each traffic light on the route at green phase. For the new problem an analytical solution has been developed. For both of the algorithms the generated velocity profiles are sent back to the vehicle and advised to the driver via additional screen attached on the dash of the vehicle. The simulation and test results have shown that the use of DP algorithm at highways and analytical solution in urban drivings would result in significant increase in fuel economy.

Coauthor(s): **Ümit Özgüner, Dimitar Filev and John Michelini** (Ohio State University)

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Title: **Voltage Stability of Weak Power Distribution Networks with Inverter Connected Sources**

Coauthor(s): **Michael Lemmon** (University of Notre Dame)

Abstract: Microgrids are small-scale power distribution systems in which generation sources are located close to loads [1]. Coupling to the main grid, microgrids encourage the consumption of locally generated power in a way that reduces peak loads seen by distribution system operators (DSOs) [2]. This method also reduces the demand for extra transmission capacities and provides a path for greater usages of renewable energy resources. Microgrids can also be operated independently from the main grid (known as islanded mode) thereby making them invaluable for loads that cannot tolerate disruptions in main grid service, such as hospitals, military bases, and remote rural areas. Microgrids, therefore, represent an important power distribution technology whose stable and efficient

operation can significantly secure power deliveries to users.

As low-voltage small-scale distribution networks, micro- grids usually have weak links. Thin cables interconnecting the buses often have a higher ratio between their conductance and susceptance, G/B, than those found in high-voltage transmission networks. A consequence of this higher ratio is that dynamics governing voltage and phase are highly cou- pled, thereby making it more difficult to guarantee voltage stability [3].

There has been a great deal of prior work studying voltage stability in weak networks [3] [4] [5] [6]. Most of those efforts, however, have studied specific network topologies, such as parallel [4] and chain [6] structures. Previous stability analysis methods include both linearization and Lyapunov approaches. Eigenvalue analysis in linearization methods only applies locally, such as in [3] [5] [6] [7]. In contrast, Lyapunov methods have been used to examine global stability [8], but the conditions derived are usually hard to check. Consequently, these prior works do not lead to an analytic set of stability constraints for weak distribution networks.

This paper is to develop constraints whose satisfaction assures frequency synchronization and voltage stability of CERTS (Consortium for Electric Reliability Technology Solutions) microgrids. CERTS microgrids [1] represent an important class of microgrids that use fast inverters to connect a heterogenous mixture of generation sources into the network. Earlier work [7] has studied the stability of relatively strong CERTS microgrids, but, to our best knowledge, there has been little work examining stability conditions for weak microgrids. Recent work [9] has attempted to address that issue by viewing the generator-connected power network as a set of coupled nonlinear oscillators, treating voltages as unmodeled random dynamics. Building upon that prior work, this paper derives a set of point-wise inequality constraints whose satisfaction assures frequency synchronization and voltage stability in an islanded CERTS microgrid. These stability conditions place constraints on interconnection weakness, requested power generations, and reactive loads. For example, an islanded microgrid consists of four subsystems, including a voltage control block, a frequency synchronization block, and two power flow relation blocks. Both frequency synchronization and voltage control blocks use droop mechanisms that down-scale conventional grid control concepts to low-voltage power networks [10]. Our stability analysis is based on the CERTS droop controllers in [1].

Based on such a system decomposition, sufficient conditions are derived in two steps for voltage stability and frequency synchronization in inverter based CERTS microgrids. This paper first identifies positively invariant sets for voltage magnitudes $\{E_i\}$ and phase angles $\{\delta_i\}$. Assuming that initial states start within these invariant sets, sufficient conditions for frequency synchronization and voltage stability are then established. The analysis to establish conditions on frequency synchronization draws upon techniques used in [9] [11]. Combined with optimal dispatch problems, these stability constraints provide a systematic framework for optimal power management in CERTS microgrids. The objective of optimal dispatching is to minimize the instantaneous operational cost of a microgrid. The optimization is subjected to constraints including power balance relations, generation capacities, cable power flow limits, voltage and frequency regulation rules, as well as stability conditions. This problem is solved by a manager to determine the optimal commanded inputs $\{P_i^*\}$ and $\{E_i^*\}$ to controllers.

Future research will focus on the optimal control of an islanded microgrid or grid-coupled microgrids, where stability constraints have been added to the constrained optimal dispatch problem. With the point-wise constraints we derived earlier, the optimal dispatch problem was solved to optimally manage microgrid operations. To deal with time-varying loads and generations, we plan to apply model predictive control (MPC) algorithms to this optimal dispatch problem. Traditionally, a control Lyapunov function (CLF) based terminal cost is used to ensure stability, which is constructed with global information, as in [12]. With the previous point-wise stability conditions, it is expected that the global terminal cost function over a finite time horizon can be replaced by a set of point-wise constraints. In addition, it is easier to distribute such constrained MPC algorithms than exchanging information between agents in order to formulating stabilizing terminal cost functions in [13].

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Title: **Robust Distributed Averaging: How to Defend Against an Intelligent Adversary?**

Author: **Ali Khanafer** (University of Illinois at Urbana-Champaign, `cercan@illinois.edu`)

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Abstract: Various physical and biological phenomena where global patterns of behavior stem from local interactions have been modeled using linear averaging dynamics. In such dynamics an agent updates its value as a linear combination of the values of its neighbors. Averaging dynamics is the basic building block in many multi-agent systems, and it is widely used whenever an application requires multiple agents, who are graphically constrained, to synchronize their measurements. Examples include formation control, coverage, distributed estimation and optimization, and flocking. Besides engineering, linear averaging finds applications in other fields. For instance, social scientists use averaging to describe the evolution of opinions in networks. While much of the literature on distributed averaging focuses on studying the convergence properties, little is known about the worst-case effects of intelligent adversaries on distributed averaging dynamics.

In this talk, we study the interaction between a network designer and an adversary over a dynamical network. The network consists of nodes performing continuous-time distributed averaging. The goal of the network designer is to assist the nodes reach consensus by changing the weights of a limited number of links in the network. Meanwhile, an adversary strategically disconnects a set of links to prevent the nodes from converging. We formulate two problems to describe this competition where the order in which the players act is reversed in the two problems. We utilize Pontryagin's Maximum Principle (MP) to tackle both problems and derive the optimal strategies. Although the canonical equations provided by the MP are intractable, we provide an alternative characterization for the optimal strategies that highlights a connection with potential theory. Finally, we provide a sufficient condition for the existence of a saddle-point equilibrium (SPE) for this zero-sum game.

Title: **Top-Down Design for Distributed Cooperative System**

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Abstract: In this talk, we would like to give a brief introduction of the current research thrusts in the Distributed Cooperative System Research Lab (DISCOVER) at Notre Dame. The main goal of DISCOVER Lab is to understand how existing natural or man-made complex systems work and, more importantly, how to build more reliable and efficient engineered complex systems, such as next-generation power grids and transportation systems. Different from the prevailing bottom-up approaches that usually preset local interactions among components and then investigate what the collective behavior would emerge from the system, we tackle the challenge from a top-down angle and explicitly design these local interactions so as to achieve certain desired collective behaviors. In particular, we are using multi-robot cooperative tasking as a particular design example to explore the design principles for distributed cooperative systems. Hopefully, the developed top-down design theory for multi-robot cooperative tasking could be extended to the design of more general cyber-physical systems and finally evolve into a scalable, correct-by-design formal approach to engineering complex systems.

Title: **Control Challenges in Unmanned Rotorcraft**

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Abstract: Unmanned rotorcraft are highly nonlinear underactuated systems with coupled dynamics. As such, controller design presents interesting challenges that need to be overcome. This talk presents the three types of controllers (linear, linearized, nonlinear) that have been proposed for non-aggressive and aggressive flights stating advantages and disadvantages and then proposes a generalized control architecture framework that may be used to accommodate flight envelope requirements, including emergency landing. Details about a nonlinear backstepping controller design are also offered.

Title: **Creating Autonomous Convoys in a Bus Network**

Author: **Ümit Özgüner** (Ohio State University, `umit@ece.osu.edu`)

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Abstract: In this talk I will present some preliminary work we have undertaken inspired by a project at Okan University in Istanbul, Turkey. The project is a feasibility study for creating autonomous convoys in an existing, segregated bus network in Istanbul, called Metrobus. The claim is that creating autonomous convoys of busses, somewhat like a light-rail system, would have advantages as far as energy, pollution and total service. Based on the above application, at the Control and Intelligent Transportation Research (CITR) Lab at OSU, we have been considering a number of related modeling and control problems. These are all preliminary studies and I present them as examples of possible control problems that can be generated from a large, cyber-physical system.

Control of Autonomous Convoys: Our approach to autonomous vehicle control has

always been using a hybrid system formulation, which makes the simulation, testing and implementation easier. Here we initiated the design process using a functional hierarchy approach so as to get the Finite State Machine portion of the Hybrid System systematically. Maintaining a multi-vehicle convoy is by now almost a standard process and many studies and demonstrations have been already done.

Energy usage and throughput with convoys: A study was performed considering energy usage of single and multiple busses going through a series of bus stops. Random arrivals were assumed for single busses, entering a finite length bus stop, where they would have to wait in a queue if the stop was full, or earlier busses were blocking access. This is a complicated problem as it combines both queue servicing at the stops and an energy usage model that is different for steady driving, stop-and-go and idling.

Human motion on the bus platform: The movement of crowds is an interesting new topic, and its simulation has been receiving a lot of attention recently. Flow models and potential field models have been considered with newer approaches like finite steps on 2-D grids. Our problem here also has some feedback control as we can open and close the bus doors and also regulate passenger entry onto the bus stop. Dealing with exiting passengers and those switching their door of choice complicate the problem further.

Acknowledgement: My thanks are due to Dean N. Tuncay and the PI, Prof. O. Alankus from Okan University for involving me in the feasibility study, the National Science Foundation supporting our work at OSU under the Cyber-Physical Systems (CPS) Program (ECCS-0931669), Dr. A. Kurt and graduate students P. Khayyer, E. Ozatay and E. Adamey at OSU for performing the investigations reported.

Title: **Control of Switched Systems with Limited Information**

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Abstract: Switched systems and control with limited information are two research areas that have evolved rapidly but separately over the last two decades. In this talk we present an attempt at their unified study, by considering a stabilization problem for a switched linear system with sampled and quantized state measurements. In our setting, at the sampling times the active mode of the switched system is known, but between the sampling times the switching signal is unknown and is only subject to mild slow-switching assumptions. An important ingredient in our stabilizing quantized feedback control strategy is the propagation of reachable set over-approximations for switched systems, a problem that has received a lot of attention in the hybrid systems literature and for which we propose a novel algorithm.

Title: **A Comparison of the Embedding Method to Multi-Parametric Programming, Mixed-Integer Programming, Gradient-Descent, and Hybrid Minimum Principle Based Methods**

Author: **Richard T. Meyer** (Purdue University, rtmeyer@purdue.edu)

Coauthor(s): **Miloš Žefran and Raymond A. DeCarlo** (Purdue University)

Abstract: Hybrid and switched systems have modes of operation. In much of the hybrid/switched system literature, modes of operation whether they be controlled or autonomous are labeled with discrete variables. In 2005, an embedding approach for solving the switched optimal control problem (SOCP) was developed by Bengea and DeCarlo [1] and later extended in [2], [3] to a special subclass of autonomous switches. The embedding approach, which converts the switched hybrid optimal control problem to a classical nonlinear optimization, has been successfully used in a variety of applications including power management of hybrid electric vehicles [4] and fuel cell hybrid vehicles [5], mobile robot slip control [6], and real-time switching control of DC-DC converters [7], [8]. For systems affine in the continuous control, the embedding approach theoretically guarantees existence of a solution under appropriate convexity of the integrand of the performance index.

The embedding approach has not been extensively compared to alternative SOCP solution approaches such as multi- parametric programming (MPP) [9], [10], academic [10] and commercial (CPLEX) [11] mixed-integer programming (MIP) implementations, or variants of gradient-descent methods [12], [13], [14], [15]. Thus our goal is to compare and evaluate the convergence time, resulting performance index (PI) costs, and requirements (e.g., requisite assumptions) of these approaches and algorithms in the context of four recently published examples: (i) spring-mass system [9], (ii) a mobile robot [12], (iii) two-tank system [13], and (iv) autonomously switched system with 11 state space regions [14], [15]. In example (i) we compare the embedding approach to MPP, MIP, and CPLEX. For examples (ii) and (iii) we compare the embedding method to gradient-descent based methods. Finally, for example (iv) we show that the minimum principle solution approach in [14] and traditional numerical programming compare favorably since the problem is one of autonomous switches that do not require a mode designation per se as described in [2].

Table I lists key differences found between the various SOCP solution approaches. From the table, the embedding method requires no specialized solvers, does not require parameterization of the autonomous switches, and does not require the input of a predefined mode sequence. Further, the embedding method allows for nonlinear affine systems (those linear in the continuous time control) whereas [9], [16] require a piecewise linear-affine approximation; in the latest implementation of the MPP method [10] the authors caution against using general nonlinear models. Finally, when the embedded solution is not bang-bang, a projection of the solution onto the feasible solutions is required (termed the projected embedding method) [17]. When the SOCP does not have a solution, the embedded solution cost is the infimum of the SOCP costs.

In the studied examples, embedding solution produced lower performance index costs than all the other optimization solutions and found solutions when the other methods failed. The projected embedding method is shown to produce lower PI costs than the other methods except in the case of a 25 partition prediction horizon spring-mass example. The difference is attributed to two factors: (i) the mode and control projection

which causes an increase in cost over the embedded cost beyond that of the CPLEX cost, and (ii) the presence of region dependent autonomous switches. In regards to point (i), a more sophisticated and rigorously developed projection method has recently been presented in [18]. In regards to point (ii), an optimal state value (as found by CPLEX) occurs at the boundary of a region defining an autonomous switch. This concurrence does necessarily occur with the numerical solver used by the embedding method. However, a finer partitioning or underlying discretization leads to the same result without a parameterization of the autonomous switching regions. We note that MPP, MIP/MPT and CPLEX explicitly parameterize regions of a controlled vector field associated with autonomous switches and hence explicitly deal with the discontinuity that results from an autonomous switch. In contrast, the Jacobian used for the embedding method is discontinuous through the boundaries of these regions causing errors in the descent to the optimum. Further, the 11 autonomous- mode switched system comparison (which did not require embedding) is shown to confirm the insight that the numerical algorithm must account for discontinuities in the vector fields either implicitly or explicitly as is done in [14], [15]. This suggests that as an area of future research, a marriage of the embedding approach with a parameterization of the regions associated with autonomous switches as is done in MIP would result in a superior algorithm with superior convergence properties. However, we stress that the basic implementation of the embedding approach as used produced solutions that were very close to those obtained by these specialized approaches; given its favorable computational complexity and ease of implementation, the embedding approach is thus particularly attractive for engineering applications.

With regards to solution times, the embedding approach is shown to have faster total solution times except in the case of CPLEX for a 3 partition spring-mass problem. We note that CPLEX is a specialized, commercial solver while the embedding method is implemented using MATLABs $fmincon$, a general nonlinear programming solver. Using a numerically superior solver would only improve the solution times (and convergence rate) of the embedding method results.

Finally, common misconceptions regarding the embedding approach are briefly addressed including whether it is necessary to tweak the algorithm to obtain bang-bang solutions (no), whether it requires infinite switching to implement embedded solution (no), and whether it has real-time capability (yes).

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Title: **Using Reachable Sets in A Game of Collision Avoidance**

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Abstract: This study focuses on developing and illustrating a collision avoidance controller, both as an advanced driver assistance system and towards limited-to-full vehicular autonomy. The selected methodology captures the behavior of a leader- follower pair of vehicles as a pursuit-evasion game. This way, the best effort of the preceding vehicle to make the follower crash (the worst case scenario) is countered with the evasive braking of the follower. Reachability analysis is utilized to calculate the regions of interest, in which the follower cannot avoid a crash with mild braking, leading to a more severe braking zone. The designed controller was illustrated through simulations.

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Title: **Receding Horizon Controllers for Switched Linear Systems: Performance Guarantees via Linear Matrix Inequalities**

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Abstract: We are interested in the control of switched linear systems; that is multi- modal systems which exhibit nondeterministic switching. The system consists of finitely many modes, each with a corresponding state-space model, and a collection of admissible switching sequences. These sequences may be developed as the output of a finite-state automaton, or may be a more general language. The resulting system dynamics are of the form

$$x_{t+1} = A_{\theta(t)}x_t + B_{\theta(t)}w_t$$
$$z_t = C_{\theta(t)}x_t + D_{\theta(t)}w_t$$

We will consider the control of switched systems to achieve two different performance measures. First, we consider the l2-induced norm of the system for disturbance attenuation. Second, we consider the average output variance over a finite window. Each performance problem allows for the performance level to vary according to the switching sequence, leading to path-by-path performance for the system. We take a receding-horizon-type approach to these problems by considering controllers with memory of finitely many past switching modes as well as a preview of finitely many future switching modes. The result is a controller which is path-dependent, whose gains are dependent on a sliding window of switching path knowledge. As the length of the observed switching path grows, the number of possible paths (and corresponding controller modes) may grow combinatorially. We begin by considering the simpler problem of uniform stabilization of switched systems without any performance measure. In this simpler setting, we demonstrate the intuition and techniques needed for the performance problems that follow. We provide exact synthesis conditions for a uniformly stabilizing controller in the form of a finite sequence of linear matrix inequalities. These inequalities are such that the feasibility of any set of inequalities provides an explicit construction for a stabilizing controller, while the infeasibility of a set of inequalities provides a lower bound on the stability radius of the system (this bound is closely related to the joint spectral radius of the underlying parameter set). We then present exact synthesis conditions for each of these performance criteria in the form of increasing sequences of linear matrix inequalities. The conditions are such that the feasibility of any one of the LMIs in the sequence provides an explicit controller satisfying the performance goal. The generalization of these conditions to path-by-path performance measures and generalized switching languages is also explored. A simple, physically-motivated example is presented to demonstrate the use of these results.

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Title: **Using Channel State Feedback to Achieve Resilience to Deep Fades in Wireless Networked Control Systems**

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Abstract: Wireless Networked Control Systems (WNCSs) comprise a number of dynamical systems that exchange information over a wireless radio communication network. Examples of such systems are found in smart transportation applications [6], unmanned aerial vehicles [5] and underwater autonomous vehicles [4] that are required to exchange in- formation to coordinate their maneuvers. These wireless communication channels, are often subject to deep fades, where a severe drop in the quality of the communication link occurs. Such deep fades will cause significant coordination loss between systems, which may lead to serious safety issues. These issues could be addressed by developing a resilient control system that detects such deep fades and adaptively reconfigures the controller to maintain a minimum performance level.

Channel fading is usually modeled as an independent and identical distributed (i.i.d) random process with Rayleigh or Rician distribution. This model is inadequate in two aspects. First, the fading process exhibits memory which is better modeled as a Markov random process with two states [7]. Second, the i.i.d. channel model ignores the impact that the system states have on the channel. Vehicle-to-Vehicle (V2V)[2] systems provide an example in which the velocity and relative distance of the vehicles significantly affect

the channel state. Moreover, for those wireless communication systems using directional antennae [8], [1], changes in the relative vehicle orientation could also lead to a deep fade.

Motivated by the V2V application, prior work [3] examined a more realistic channel fading model in which the channel is exponential bursty and is dependent on the norm of physical systems states. Assuming such fading channel, necessary and sufficient conditions are established to assure almost sure stability for linear WNCSs. These conditions used channel state information (CSI) as a feedback signal to reconfigure the controller to recover system performance in the presence of deep fades.

This paper extends the results in [3] to a two dimensional leader follower control problem using directional antennae to access the wireless communication network. For example, the geometry of a leader-follower system: the ith vehicle's position (i=1,2) at time $t \in \mathbb{R}_+$ is denoted by $(x_i(t), y_i(t))$. The attitude of the vehicle relative to the $y = 0$ axis at time t is denoted as $\theta_i(t)$. The position and attitude trajectories satisfy the differential equations

$$\dot{x}_i = v_i \cos(\theta_i), \quad \dot{y}_i = v_i \sin(\theta_i), \quad \dot{\theta}_i = \omega_i,$$

where the control inputs, v_i and ω_i, are the vehicle's speed and angular velocity, respectively.

The leader can directly measure its bearing angle, α relative to the follower. Similarly, the follower can measure its bearing angle, ϕ, relative to the leader. Both vehicles can measure the distance, L between the vehicles. What is not directly known by the follower is the leaders relative bearing angle,α. The leader will transmit the quantized α to the follower over a wireless channel that is accessed using a directional antenna. The wireless channel is exponential bursty and is dependent on the system state L and α. The control objective is to have the follower adjust its velocity, v_i and angular rate ω_2, to achieve and maintain a desired inter-vehicle distance, L_d, and relative bearing angle, α_d.

This paper studied the almost-sure stability for leader- follower formation control of nonholonomic systems in the presence of deep fades exhibiting exponentially bounded burstiness. Sufficient conditions are established to use CSI to switch the controller to assure almost-sure asymptotic stability. The simulation results clearly demonstrate the necessity of using CSI to achieve resilience to deep fades. Future work will extend these concepts from leader-follower formations to more general formation control problems, for instance, vehicular platoon control problem.

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Title: **Opportunistic Sensor Activation in the Face of Data Deluge**

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Abstract: In this paper, we consider the problem of optimal measurement policies for a sensor that acquires sequential compressive measurement of a static vector of unknown sparsity. We explore the problem of optimizing the measurement policy in finite horizon sequential compressive sensing when the number of samples are strictly restricted to be less than the overall horizon of the problem. We assume that at each instant the sensor can decide whether or not to take an observation, based on the quality of the sensing parameters. The objective of the sensor is to minimize the coherence of the final sensing matrix. This problem lies at the intersection of usage limited sensing [2], [3] and sequential compressive sensing [1]. We present optimal open-loop and closed-loop measurement policies for a low-dimensional problem. We generalize the optimal policy to obtain a feasible policy for acquiring arbitrary length sparse vectors of unknown sparsity.

Title: **Communication with Delay Constraint in Event Triggered System**

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Abstract: The selection of the period must guarantee system performance in various operating conditions and thus may become very conservative. Motivated by this problem, event-triggering scheme has been proposed in which information is sent only when the system states exceed some specified threshold. In this way, stability can be achieved while saving communication resources. The stable operation of event- triggered schemes impose delay constraints on message delivery. Such constraints can be difficult to enforce over

wireless channels. This work uses an exponential burstiness framework for modeling channel latencies and analyzing the control systems almost-sure stability.

Title: **Efficiently Attentive Event Triggered Wireless Sensor-Actuator Networked Systems with Limited Bandwidth**

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Abstract: Event triggering has experimentally shown its potential to reduce communication frequency while maintaining compa- rable performance as periodic triggering[1], [2]. Generally speaking, the event that triggers a transmission is always designed as data novelty exceeds a specified threshold. In [3], for example, the data novelty is defined as the norm of the gap between the current state and the last sampled state, and the threshold is defined as a linear function of the norm of the current state. With such defined event, it was shown that the inter-sampling interval in homogeneous systems got longer as the system state got closer to the origin [3]. We call this property efficient attentiveness. Efficiently attentive systems transmit less often in steady processes than in transient processes. This is desirable for systems who stay in their steady processes for most of the time. However, not all event triggered systems are efficiently attentive.

For wireless networks with limited bandwidth, the usage of communication resources is characterized by not only inter-sampling interval but also instantaneous bit-rate. Instantaneous bit-rate is the ratio of number of bits in each packet to the acceptable delay of this packet. Inter-sampling interval and instantaneous bit-rate respectively characterize how often and how much the communication resources are used. Therefore, for systems in wireless networks with limit- ed bandwidth, efficient attentiveness means not only that the inter-sampling interval gets longer, but also the instantaneous bit-rate gets lower, as the system state approaches zero.

This paper presents a sufficient condition for efficient attentiveness in wireless sensor networks with limited band- width. We first provide an event trigger and a quantizer guaranteeing input-to-state stability (ISS) assuming there is no delay. The acceptable delay is then studied to preserve the ISS. Different from the prior work [4], [5] which considered constant bounded delay, the acceptable delay we find is state dependent. Finally, a sufficient condition of efficient attentiveness is given.

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