Control Systems and the Quest for Autonomy

A Symposium in Honor of Professor Panos J. Antsaklis

October 27–28, 2018

University of Notre Dame

https://sites.nd.edu/autonomy-symposium

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Control Systems and the Quest for Autonomy

Excerpt from: *P. Antsaklis, "Editorial: Control Systems and the Quest for Autonomy," IEEE Transactions on Automatic Control, vol. 62, no. 3, pp. 1013–1016, Mar. 2017.*

. . . On a personal note, the above ideas influenced and guided my research for decades, where I pursued research in learning via neural networks, in DES supervisory control via Petri nets, in the control of hybrid dynamical systems, in networked control systems, and more recently in Cyber-Physical Systems.

I am convinced that there are tremendous opportunities for Systems and Control specialists in the area of Autonomous Systems. Of course this is a long held belief of mine as witnessed by my intensive research in the area, and by my earlier attempts to draw your attention to these opportunities. In fact, the closing comments of my first Editorial as the Editor-in-Chief of the IEEE TRANSACTIONS ON AUTOMATIC CONTROL in January 2010 [item 1) in the Appendix] were:

> Throughout my professional career I have been a firm believer first in the Quest for Autonomy as a powerful driving force in engineered systems over the centuries, and in Feedback as the best mechanism to achieve autonomy, witnessed by feedback's ubiquitous presence in all natural and human made systems. I have been including these themes in my talks for many years. In our chosen field of Systems and Control we should go beyond emphasizing exclusively only certain types of models and mathematical techniques. We need to see the bigger picture, to realize that there are many ways to describe the phenomena we want to control, involving for example logic in addition to differential equations, as in hybrid systems, and expanding our horizons and our field. And this will happen if in our theoretical research we are also motivated by application needs and not only by mathematical challenges. We have very much to offer, and we should work towards realizing this potential.

And in my 2013 Editorial [item 2) in the Appendix] I wrote:

> We need to address bigger problems. A system typically is more than a set of ODEs and the specs may not be conveniently described in the frequency domain. While these specs served us well in the past and are still very useful, we need to move on because the problems and their descriptions have become much more sophisticated and much more demanding. We are in the systems area after all, an area that prides itself for considering a wider view of the problem, taking a system's, a bird's eye point of view. In hybrid dynamical systems we combine discrete and continuous dynamics to study the system behavior. Nowadays we have data and lots of it that need to be considered together with our mathematical models. What is the best way to go? This is quite a challenge.

We, in Systems and Control, can be the most important contributors to autonomous systems with our knowledge of feedback (feedback is important throughout, at all levels of autonomous systems; remember that feedback transcends models), our mathematical expertise, and with our fundamental understanding of dynamical systems and their interactions. Let's do it! Yes, we can!

1) P. J. Antsaklis, "Continuing the tradition of excellence in 2010 and beyond," IEEE Trans. Autom. Control, vol. 55, no. 9, pp. 13, Jan. 2010. [pdf]

2) P. J. Antsaklis, "Continuing the tradition of excellence: Where we have been and where we could go," IEEE Trans. Autom. Control, vol. 58, no. 9, pp. 21572159, Sep. 2013. Part of this editorial was published under the title, "Some thoughts about publishing results in our field," IEEE Control Syst. Mag., pp. 2241, vol. 33, no. 6, Dec. 2013. [pdf]

Program

Saturday October 27

1:00 PM	K. Passino, T. Fuja, G. Snider, P. Antsaklis, X. Koutsoukos, M. Xia	Welcome and Introductions
1:30 PM	Kimon Valavanis	University of Denver
	On Using Entropy as a Unified Measure to Evaluate Autonomous Functionality of Hierarchical Systems	
1:45 PM	Janos Sztipanovits	Vanderbilt University
	Is Science in System Integration?	
2:00 PM	Jay Farell	University of California at Riverside
	Reliably Accurate State Estimation for Connected and Autonomous Highway Vehicles	
2:15 PM	Michael Lemmon	University of Notre Dame
	Equation-free Supervision of Coherent Structures in Complex Dynamical Networks	
2:30 PM	Nitesh Chawla	University of Notre Dame
	Modeling Higher Order Dependencies in Complex Systems	
2:45 PM	John Baras	University of Maryland
	Trusted Autonomy	
3:00 PM		**Break**
3:30 PM	Trevor Williams	NASA Goddard Space Flight Center
	Formation Flying Dynamics and Control for the MMS Mission: Flight Experience	
3:45 PM	Eloy Garcia	Air Force Research Laboratory
	Cooperative teams and differential games	
4:00 PM	Michael McCourt	University of Washington Tacoma
	Nonlinear analysis for control and estimation of human-machine teams	
4:15 PM	Michael Sartori	Venable LLP
	Control Through Intellectual Property	
4:30 PM	A. Michel, P. Antsaklis	Getting to know Panos Antsaklis

Program

Sunday October 28

9:00 AM	Kevin Passino *Autonomy for the Others*	The Ohio State University
9:15 AM	Hai Lin *Challenges in achieving long-term autonomy*	University of Notre Dame
9:30 AM	Zhiqiang Gao *From the Autonomy of Control to the Autonomy of "Disturbance" Rejection*	Cleveland State University
9:45 AM	Yue Wang *Trust-based Motion Planning, Decision Making and Control of Human-Robot Collaboration Systems*	Clemson University
10:00 AM		**Break**
10:30 AM	Vijay Gupta *Data-driven identification of control-oriented models for passive systems*	University of Notre Dame
10:45 AM	Hasan Zakeri, Yang Yan, Etika Agarwal *Recent results in resilient CPS design using passivity and dissipativity*	University of Notre Dame
11:00 AM	Getachew Befekadu *On the asymptotics of exit problems for controlled Markov diffusion processes with random jumps and vanishing diffusion terms*	Morgan State University
11:15 AM	Luis Montestruque *A Distributed Control Application to Urban Drainage Systems*	EmNet LLC.
11:30 AM	Nick Kottenstette *A Secure Robotics Platform for Remote Vascular Interventions Including PCI and Stroke*	Corindus Vascular Robotics
11:45 AM	Meng Xia *Lane Following Control with Sensor Fusion and Lane Detection*	The Mathworks
12:00 PM	Xenofon Koutsoukos *Adversarial Regression for Detecting Attacks in Cyber-Physical Systems*	Vanderbilt University
		Closing

On Using Entropy as a Unified Measure to Evaluate Autonomous Functionality of Hierarchical Systems

Kimon Valavanis **Saturday 1:30 PM**

The Entropy based approach to modeling and performance evaluation of Intelligent Systems/Machines (IMs), which are modeled as hierarchical, multi-level structures is presented. A chronological summary of developments related to intelligent control, from its origins to current advances is discussed first, followed by definitions of autonomy and intelligence, to be exact, machine intelligence for engineering systems, which set the foundations necessary to tackle related challenges. A multi-level, hierarchical, functional architecture is then described and used to model and control complex systems. The duality of the concept of Entropy as a measure of uncertainty and as a control function is introduced to model, control, evaluate and improve through adaptation and learning performance of engineering systems. The modeling philosophy for the systems under consideration follows the mathematically proven principle of Increasing Precision with Decreasing Intelligence (IPDI). Entropy is also used in the context of N-Dimensional Information Theory to derive a Generalized Law of Information Rates, which models the flow of information throughout such systems and contributes to quantitatively evaluate uncertainty, thus, autonomy and intelligence. A candidate intelligent robotic system (IRS) is considered for clarification and demonstration purposes, and to also illustrate how Entropy qualifies as a unique, single, measure to model/evaluate autonomy, intelligence and precision of task execution. The main contribution of this talk is that it aims to bring under one forum major research findings starting in the 1970s and 1980s, and to support the argument that even today, given the unprecedented existing computational power, advances in Artificial Intelligence, Deep Learning and Control Theory, the same foundational framework may be followed to study large-scale, distributed Cyber Physical Systems (CPSs), including distributed intelligence and multi-agent systems, with direct applications to the SmartGrid, transportation systems and multi-robot teams, to mention but a few applications.

Is Science in System Integration?

Janos Sztipanovits **Saturday 1:45 PM**

System integration is frequently considered to be the most risky and most expensive phase of system development. Yet, the problems are undervalued scientifically and swapped aside as an ad-hoc activity to get the system going somehow. The unique challenges in CPS integration emerge from the heterogeneity of components and interactions. The ideal design flow in CPS is model-based and correct-by-construction: the results of the design process are verified models that predict system behavior after implementation with high accuracy. Unfortunately, heterogeneity and separation of design concerns defeats this idea. Actual design flows are construct-by-correction: problems come up during the integration phase that need to be fixed using many iterations. In a joint project performed by Vanderbilt University, University of Notre Dame and University of Maryland we have investigated methods to make system integration less risky by introducing theoretically well founded methods to decouple design concerns. The results of the project was the systematic introduction of passivity-based design that was built to a great extent on the groundbreaking work of Professor Antsaklis. In this talk I will review the key questions in the project and highlight key tenets of passivity-based design.

Reliably Accurate State Estimation for Connected and Autonomous Highway Vehicles

Jay Farrell **Saturday 2:00 PM**

Accurate and reliable awareness of world interactions is a key requirement for effective commercial deployment of autonomous and connected vehicles. Awareness arises from onboard sensors and ubiquitous communication between vehicles and infrastructure. Vehicle coordination and safety necessitate reliable where-in-lane knowledge of vehicle position. This presentation will address sensor fusion for high-bandwidth vehicle state estimation with a focus on high accuracy and reliability.

Advances is sensing and computation have dramatically altered the focus of related research. For example, either computer vision or Global Navigation Satellite Systems separately provide far more measurements than are necessary for observability. The large number of measurements provides both opportunities (e.g., high accuracy) and challenges (e.g., large numbers of outliers). Standard state estimation approaches that decide irrevocably at each time which

measurements are valid (e.g. EKF) are not sufficiently reliable at removing the effects of spurious measurements. When that decision is wrong, either measurement information is lost or the state and covariance estimates become corrupted, rendering all subsequent decisions suspect. Either situation can result divergence of the state estimate.

This presentation will introduce an alternative approach called risk-averse performance-specified (RAPS) state estimation that solves an optimization problem to select the least risky set of measurements that satisfies a user-defined performance constraint. Such methods may be combined with approaches that extract the Bayesian optimal trajectory using all sensor data over a temporal window (e.g. SLAM and RHE) while minimizing risk subject to accuracy constraints. Such approaches are able to evaluate and reconsider outlier assumptions for all measurements within the temporal window.

Equation-free Supervision of Coherent Structures in Complex Dynamical Networks

Michael Lemmon **Saturday 2:15 PM**

"Equation-free" refers to methods that use trajectory data or microscopic-level simulation models to identify coherent structures in networked dynamical systems. This talk reviews one method for identifying such coherent structures based on a discrete abstraction of the process. We go on to demonstrate how the problem of managing transitions between such structures may be viewed in terms of supervisory hybrid control; thereby linking these methods back to Dr. Antsaklis' prior work regarding interface design in hybrid systems.

Modeling Higher Order Dependencies in Complex Systems

Nitesh Chawla **Saturday 2:30 PM**

Trusted Autonomy

John Baras **Saturday 2:45 PM**

Autonomous systems are becoming ubiquitous in both DoD missions as well as in several expansive commercial markets. Accurate (and verifiable) prediction of such complex systems behavior and performance is extremely challenging. We describe new foundational methods for embedding in system design and operation self-learning, self-monitoring, self-assessment, self-correction, so that the autonomous systems can adjust their tasks and behaviors as needed, due to changes in the environment or in their own functionality. Such capabilities are essential for autonomous systems. We discuss briefly the following components of the new methodology: Enhancement of our rigorous model-based systems engineering methodology and framework with novel hierarchical monitoring methods for performance correctness and safety, and novel formal models and proof methods for safety assurance during learning and adaptation; Synthesis and operation of autonomous systems under spatial and temporal safety constraints, based on a combination of set-valued dynamics (reachability analysis) and finite time temporal logics (metric temporal logic).

Formation Flying Dynamics and Control for the MMS Mission: Flight Experience

Trevor Williams **Saturday 3:30 PM**

The NASA Magnetospheric Multiscale (MMS) mission involves flying four spacecraft in tight formations on highly elliptical orbits in order to study the heliophysics phenomenon of magnetic reconnection. Such formations have complicated dynamics and are consequently difficult to control, particularly as regards the prevention of close approaches between the satellites. The flight experience of MMS since its launch in Mar. 2015 will be discussed, and conclusions drawn for autonomy and future smallsat missions.

Cooperative teams and differential games

Eloy Garcia **Saturday 3:45 PM**

With the increasing number of applications involving multiple unmanned aerial vehicles (UAVs), a significant effort has been made to design and analyze cooperation and coordination methods for different types of missions. Task allocations, search and track, and intelligence, surveillance, and reconnaissance (ISR) missions are some of the common applications that have been addressed using cooperative UAVs. In this talk, dynamic problems related to combat and protection of valuable targets will be considered within the context of differential games. The goal is to design and verify saddle-point state feedback strategies for each player highlighting the advantages of cooperation and coordination among members of a team.

Nonlinear analysis for control and estimation of human-machine teams

Michael McCourt **Saturday 4:00 PM**

Modern control systems have grown in scale and complexity and often contain a human-in-the-loop or human-on-the-loop for safety and reliability. Rather than being an impediment to control performance, the strengths of the human can be leveraged for more reliable performance. This combination of a traditional autonomous controller and a human controller can be termed "semi-autonomous". The focus of this talk is on nonlinear analysis methods (passivity and dissipativity) applied to estimation and control problems in semi-autonomous teams. There have been some promising results in using these nonlinear methods to guarantee stability and stability margins in control synthesis. These results have been applied to real world problems by considering the effects of communication networks, switching dynamics, and human reaction time delay. Each of these complications has a unique approach which leads to a holistic approach to design of human-machine teams.

Control Through Intellectual Property

Michael Sartori **Saturday 4:15 PM**

An introduction to intellectual property is provided, including patent, copyright, trade secret, and trademark law. Further concepts are explored regarding patents: inventions that can be legally protected through patenting; determining ownership of the patent rights; the process for obtaining patent protection from the U.S. Patent and Trademark Office; and the bundle of legal rights included with patents.

Autonomy for the Others

Kevin Passino **Sunday 9:00 AM**

Feedback control systems that achieve various levels of autonomy have become a necessity for all people, especially those in dire poverty or poor mental health. In this talk, two examples of where feedback control is greatly needed are outlined: (i) for individual/community financial advisors to avoid financial tragedy for persons living in poverty; and (ii) for persons with mental illnesses such as emotion/mood regulation deficiencies (e.g., depression). It will be shown that there are little-explored opportunities for mathematical analysis (e.g., conditions for stability that represent the ability to lift mood out of a depressed state) and computational studies (e.g., simulations that show that community finance management strategies are robust and successful) that will enable controller design.

Challenges in achieving long-term autonomy

Hai Lin **Sunday 9:15 AM**

How to achieve long-term autonomy is a fascinating research area at the intersection of robotics, control, information theory and computer sciences. In this talk I aim to share some thoughts from a control theoretician on the challenges in achieving long-term autonomy. Motivated by these new challenges, I will further report some of our research activities towards our long-term research goal build fundamental design theory enabling intelligent physical systems that can accomplish non-trivial high-level complex missions in a correct-by-design manner, be robust to unpredictable uncertainties, be resilient to unexpected failures, and be adaptive to dynamic environments.

From the Autonomy of Control to the Autonomy of "Disturbance" Rejection

Zhiqiang Gao **Sunday 9:30 AM**

Control is made automatic, as commonly explained, by the central idea of close-loop, i.e. adjusting the action according to its consequence. In reality, physical processes are constantly disturbed, internally and externally, severely limiting the operating range of autonomy. Scholars and practitioners alike have asked for ages if these unknown and unpredictable forces can be handled with autonomy, releasing engineers from endless tasks of tuning, measuring and modeling, etc. In this talk, we trace several strands of ideas of such autonomy, from Poncelet's Isochronous Governor to Hans Auto Disturbance Rejection, from their incubation period to their modern rendition, and to the profound impact on our fundamental understanding of automatic control.

Trust-based Control, Decision-Making, and Motion Planning for Human-Robot Collaboration Systems

Yue Wang **Sunday 9:45 AM**

Robots and autonomous systems are becoming an essential component that empowers economic and human possibility. The talk will begin with an overview of current research projects at the Interdisciplinary & Intelligent Research (I2R) lab in the Mechanical Engineering Department at Clemson University. Human-robot collaboration integrates the best part of human intelligence with the advantages of robotic systems. This talk will then introduce background and motivation of human-robot interaction and especially human trust in robots. Next, the research contributions of I2R in this field will be presented which include computational trust modeling, mutual trust based bilateral haptic teleoperation of unmanned aerial vehicles and unmanned ground vehicles, as well as trust-based human-robot collaborative assembly in manufacturing. The I2R laboratory facilities and robot experiments will be demonstrated. The talk will conclude with a discussion about future research and collaboration.

Data-driven identification of approximate passive linear models for nonlinear systems

Vijay Gupta **Sunday 10:30 AM**

We consider the problem of identifying a passive linear model of an unknown passive nonlinear system from time domain input-output data. Standard regression techniques to identify approximate linear models of a nonlinear system may not preserve properties such as passivity. We identify a method to perturb the system matrices of the linear model to enforce passivity while ensuring that the linear model closely approximates the dynamical behavior of the nonlinear system.

Recent results in resilient CPS design using passivity and dissipativity

Hasan Zakeri, Yang Yan, Etika Agarwal **Sunday 10:45 AM**

Resilient Cyber-physical systems have been a major topic of research in Notre Dame for several years. Antsakliss group have adopted energy like concepts of passivity and dissipativity as the central concept to design resilient Cyber-physical systems. In this presentation, we will briefly go over recent findings and ongoing projects in this group. Introduction of new concepts to better analyze complex systems plus innovative design techniques for interconnected systems as well as security in design and estimation will be major topics of this brief talk.

On the asymptotics of exit problems for controlled Markov diffusion processes with random jumps and vanishing diffusion terms

Getachew Befekadu **Sunday 11:00 AM**

In this talk, we present the asymptotics of exit problems for controlled Markov diffusion processes with random jumps and vanishing diffusion terms where the random jumps are introduced in order to modify the dynamics of the

controlled Markov diffusions by switching from one mode to another, i.e., depending on the state position and transition, the dynamics stochastically switching between the different drift and diffusion terms. In particular, we study the asymptotic exit problem concerning such controlled Markov diffusion processes in two steps: (i) First, for each controlled Markov diffusion process, we look for an optimal Markov control process that minimizes the principal eigenvalue of the corresponding infinitesimal generator with zero Dirichlet boundary conditions, where such an optimal control process also forces the controlled Markov diffusion process to remain in a given bounded open domain, at least on the average, for as long as possible. (ii) Then, using large deviations theory, we determine the exit place and the type of distribution at the exit time for such controlled Markov diffusion processes with random jumps and vanishing diffusion terms. Moreover, the asymptotic results at the exit time also give us the limiting behavior of the Dirichlet problem for the corresponding system of elliptic PDEss with a vanishing small parameter in the higher derivatives. Finally, we briefly discuss the implication of our results.

A Distributed Control Application to Urban Drainage Systems

Luis Montestruque **Sunday 11:15 AM**

Urban drainage systems are transport networks that carry wastewater or a combination of wastewater and storm water from homes and businesses to treatment facilities prior to being discharged to the environment. These systems are significantly affected by rainfall events that can overwhelm the treatment plan. In particular, Combined Sewer Overflows (CSO) are a major environmental challenge for more than 700 cities in the United States. Combined sewer systems are designed to shed the excess flow by releasing untreated wastewater directly into neighboring rivers or streams in order to prevent street and basement flooding. According to the USEPA, CSOs are responsible for the release of more than 3200 cubic kilometers of untreated sewage into rivers, lakes, and oceans.

This presentation describes a distributed wireless cyber physical system (CPS) that is used to manage a metro-scale water drainage system. The system consists of 150 sensors and 12 actuators installed in the sewers of South Bend, Indiana, U.S.A. Using an agent-based distributed control system, the control system reduces rain-induced overflows of untreated sewage into the river by dynamically controlling flows as they flow through the network of sewer pipes, pump stations and other infrastructure.

The presented solution attempts to take advantage of existing conveyance and storage capacity of the collection system as storm events present high temporal and spatial variability which, at any point in time, exceeds the hydraulic capacity of some assets while underutilizing others. By taking advantage of underutilized assets, the system is able to redirect flows from areas that are overwhelmed to areas with lesser hydraulic loads.

A Secure Robotics Platform for Remote Vascular Interventions Including PCI and Stroke

Nick Kottenstette **Sunday 11:30 AM**

In 1964, vascular radiologist, Charles Dotter performed the first percutaneous transluminal angioplasty under x-ray guidance by increasing the diameter of the arteries in patients suffering from arteriosclerosis in peripheral arteries of their legs by inserting catheters of increasing diameter. In 1977 German cardiologist Andreas Guentzig performed the first percutaneous coronary angioplasty. These interventions are considered non-invasive as they do not require the patient to require surgery to gain access to their diseased artery or vessel. However, these interventions come at a price to both the physicians occupational health and patient who are subject to direct and indirect radiation respectively. The physician must wear lead and eye radiation protection. In order to remove the physician from the direct radiation of the fluoroscope, a Remote Navigation System (RNS, NaviCath, Haifa, Israel) was developed by Rafael Beyer, MD in 2004. Together with Tal Wenderow, they showed that the RNS could be used to successfully navigate a guide wire past a coronary lesion, deliver a balloon catheter over a guide wire to the lesion to perform angioplasty and deploy a stent to the diseased artery in the patient.

Together, they co-founded Corindus Vascular Robotics which first received FDA approval for robotic PCI in 2012 with its CorPath 200 . The CorPath 200 allows the physician to robotically navigate a guide wire past a lesion, perform angioplasty and deliver treatment such as a stent to a diseased artery. The procedure is performed by the physician from a control console while seated behind a lead lined cockpit in the catheterization lab. A guide catheter is used to access either the left or right ostium of the coronary arteries. While navigating a guide wire past a lesion the guide catheter may unseat, possibly requiring the physician to leave their control console, and move to the table to reseat the guide catheter in the patient. To allow the physician to remain seated at their control console and

maintain control of the guide catheter position, Corindus developed the CorPath GRX , which received FDA approval in 2017. In 2017, Dr. Ryan Madder published that in principle the physician could complete a PCI procedure without having to interact directly with the patient using the CorPath 200. Although the trial removed the physician from the catheterization lab, the overall range was limited to the field bus cable length. To address these limitations, a proof of principal secure remote robotics platform was developed to enable the physician to perform remote vascular interventions over LAN, MAN or WAN networks. This platform was used to do ex-vivo and in-vivo PCI studies in cardiac models over distances up to 100 miles. Using these types of technologies, access to care has the potential to be greatly improved and thereby reduce the time required to treat a patient with either a heart attack or stroke. This reduced time to intervention may have profound effects in the patients outcomes.

The system includes : i) the CorPath GRX robotic system; ii) a secure networking platform to send robotic command and control information while monitoring real time fluoroscopic images; iii) a PTP networking system to provide round trip command and imaging delay to the physician; iv) a patient health monitoring system which includes hemodynamic information; and v) an audio and video conferencing system to immerse the physician, support staff and patient in the overall intervention.

Lane Following Control with Sensor Fusion and Lane Detection

Meng Xia **Sunday 11:45 AM**

In this talk, we present a lane following control system with sensor fusion and lane detection. The lane following controller is designed using model predictive control. The surrounding cars and roads are modeled by synthetic data from vision and radar detections. The lane following system estimates lane center and lead car to control longitudinal acceleration and steering angle of the ego car. The designed lane following controller can be verified through standard and real-world scenarios in closed-loop simulations.

Adversarial Regression for Detecting Attacks in Cyber-Physical Systems

Xenofon Koutsoukos **Sunday 12:00 PM**

Attacks in cyber-physical systems (CPS) which manipulate sensor readings can cause enormous physical damage if undetected. Detection of attacks on sensors is crucial to mitigate this issue. Supervised regression can be used as a means to detect anomalous sensor readings, where each sensors measurement is predicted as a function of other sensors. We show that several common learning approaches in this context are still vulnerable to stealthy attacks, which carefully modify readings of compromised sensors to cause desired damage while remaining undetected. Next, we model the interaction between the CPS defender and attacker as a Stackelberg game in which the defender chooses detection thresholds, while the attacker deploys a stealthy attack in response. We present a heuristic algorithm for finding an approximately optimal threshold for the defender in this game, and show that it increases system resilience to attacks without significantly increasing the false alarm rate.

Organizers

General chairs:	**Dr. Kevin Passino,** The Ohio State University **Dr. Xenofon Koutsoukos,** Vanderbilt University
Program Chair:	**Dr. Meng Xia,** Mathworks
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Notes