Pacific Northwest
NATIONAL LABORATORY

# Control Day at PNNL

August 29, 2018 | Discovery Hall

Pacific Northwest National Laboratory (PNNL)

Richland, WA

**Hosted by PNNL's Control of Complex Systems Initiative (CCSI)**

U.S. DEPARTMENT OF
ENERGY

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# Welcome

**…to Control Day at Pacific Northwest National Laboratory (PNNL)!** This event, hosted by PNNL's Control of Complex Systems Initiative (CCSI), showcases PNNL-developed control capabilities and technologies that may have applications in a variety of research at the Laboratory, as well as externally. While CCSI's control-related research has focused on developing capabilities for large infrastructures (the power grid, buildings, transportation systems, etc.), a number of other research fields, such as computation and biology, potentially could benefit from the advances.

In addition to researchers at PNNL who are attending this event, we graciously welcome our guest speakers and other representatives of government, industry and academia who are joining us. We are pleased that you are here providing updates on your research, learning more about our work, and perhaps gaining insights into how we might partner in the future to address national science and technology needs. Although CCSI ends its five-year run as an initiative on September 30, PNNL's control-related research and desire to collaborate and develop solutions will continue for years to come.

## Meet the CCSI Leadership Team

**Michael Brambley**
Initiative Lead

**Hong Wang**
Initiative Co-Lead, Chief Scientist

**Draguna Vrabie**
Theory Focus Area Lead

**Thomas Edgar**
Tools Focus Area Lead

**Mark Rice**
Test Bed Focus Area Lead

**Jason Fuller**
Demonstrations Lead

**Karan Kalsi**
Outreach Lead

**Sherry Kowalski**
Project Coordinator

**Jennifer Lee**
Commercialization and IP

**Tim Ledbetter**
Communications

### With Gratitude…

CCSI thanks the following for their support and contributions over the past five years:

- CCSI principal investigators and their project teams
- Past and existing CCSI Advisory Committee members
- PNNL's Deputy Director for Science and Technology, Laboratory Directed Research and Development program, and Energy and Environment Directorate (EED) leadership
- Managers and staff across EED and in other PNNL directorates, including the National Security Directorate and Earth and Biological Sciences Directorate, who played key roles in the success of CCSI.

# Agenda

**Wednesday, August 29, 2018 | 11:30 a.m. – 6:30 p.m.**
**Discovery Hall | 650 Horn Rapids Road | Richland, WA 99354**

| Time | Topic | Location |
|---|---|---|
| 11:30 am – 12:00 pm | **Registration & Networking** | Lobby |
| 12:00 – 12:30 pm | **Welcome/What you will see and hear today**<br>*Dr. Michael Brambley, PNNL* | Horizon C |
| **Transportation** | | |
| 12:30 – 1:00 pm | **Consensus-Based Coordination of Electric Vehicle Charging Considering Transformer Hierarchy**<br>*Guest Speaker: Prof. Ian Hiskens, University of Michigan* | Horizon C |
| 1:00 – 1:30 pm | **Control of Fully Connected Transportation Systems: Challenges and Opportunities**<br>*Dr. Jamie Lian, PNNL* | Horizon C |
| **Biological Systems** | | |
| 1:30 – 2:00 pm | **Discovery and Characterization of Novel Feedback Control Mechanisms in Synthetic Gene Networks: From Principled Models to Deep Learning**<br>*Guest Speaker: Prof. Enoch Yeung, University of California, Santa Barbara* | Horizon C |
| 2:00 – 2:30 pm | **Break**<br>*(and visit the demos and posters)* | Lobby |
| **Electric Power Grid** | | |
| 2:30 – 3:00 pm | **Tie-line Scheduling in Electric Power Systems Under Uncertainty**<br>*Guest Speaker: Prof. Subhonmesh Bose, University of Illinois at Urbana-Champaign* | Horizon C |
| 3:00 – 3:30 pm | **Distributed Controls for Electric Power Grid Modernization**<br>*Dr. Tom McDermott, PNNL* | Horizon C |
| 3:30 – 4:00 pm | **High Performance Computing for Optimization and Control of Energy Systems**<br>*Dr. Henry Huang, PNNL* | Horizon C |

| Demonstrations, Posters, Networking Mixer | | |
|---|---|---|
| 4:00 – 5:30 pm | **Demonstrations and Posters of PNNL Controls Work** – *See list of Demonstrations and Posters for more details.* | Lobby |
| 5:30 – 6:30 pm | **Networking Mixer** | Lobby |

# Master of Ceremonies

**Dr. Michael Brambley** possesses more than 35 years of academic and research experience related to energy technologies and policy, focusing for the past 30 years at PNNL on development of technologies for improving the energy efficiency of engineered systems. Dr. Brambley has served in a variety of roles at PNNL, including principal investigator and research contributor, project and program manager, technical group leader, department chief scientist, and a leader in several initiatives, including CCSI. Most of his work over the past 15 years has focused on improving the actual operating efficiency of buildings and other energy systems. For six years before joining PNNL, Dr. Brambley was a faculty member at the Washington University Engineering School in St. Louis.

Dr. Brambley will provide an overview of the day's events and introduce Control Day Speakers.

# Presentations: Speaker Biographies and Abstracts (in speaking order)

**Prof. Ian Hiskens** is the Vennema Professor of Engineering in the College of Engineering at the University of Michigan. He also serves as a professor of Electrical Engineering and Computer Science. Dr. Hiskens' research interests include power system analysis, and analysis and control of nonlinear non-smooth dynamical systems. His areas of specialty are power system dynamics and control, wind power, grid controllability, and inverse problems.

### Presentation:
### "Consensus-Based Coordination of Electric Vehicle Charging Considering Transformer Hierarchy"

Dr. Hiskens' presentation examines the coordination of electric vehicle (EV) charging where the loading on the transformers that serve the distribution feeders is taken into account. A decentralized control method is designed such that self-interested EVs are motivated to achieve global benefits. The formulation has a hierarchical structure. At the lower level, each transformer broadcasts a price signal to the EVs that it supplies, and the EVs individually determine their optimal charging strategies. At the upper level, the communication network between transformers is described as a graph and a consensus algorithm among the transformers is used to obtain a group consensus price that reflects the system generation cost. Each transformer then establishes a price which is composed of the consensus price together with a contribution that accounts for its loading characteristic. An update algorithm is developed which converges in a few (typically around ten) iterations to the unique and efficient (socially optimal) solution.

**Dr. Jianming (Jamie) Lian** received his B.S. degree with the highest honor from University of Science and Technology of China in 2004. After that, he earned M.S. and Ph.D. degrees in Electrical Engineering from Purdue University in 2007 and 2009, respectively. From 2010 to 2011, he worked as a postdoctoral research associate at the Center for Advanced Power Systems, Florida State University, where he was involved in various projects related to the development of a future all-electric ship supported by the U.S. Office of Naval Research. He is currently a staff engineer in the Optimization and Control group at Pacific Northwest National Laboratory (PNNL). His research interests mainly focus on the application of distributed optimization and control to large-scale complex systems. At PNNL, he has served as a project manager, principal investigator(PI)/Co-PI and a key technical contributor for many research projects in the areas of the power grid, building systems, and transportation systems. In particular, he has been extensively working on the development of the theoretical foundation for the new market-based framework to engage and integrate various distributed energy resources (DERs) into the future distribution management system. He has published more than 45 peer-reviewed journal and conference papers, one book chapter and many technical reports, and has also filed four patents.

## Presentation:
## "Control of Fully Connected Transportation Systems: Challenges and Opportunities"

The transportation system is going through constant evolution. Many new technologies enabled by V2V, V2I, and V2X communications are emerging in the market with the ultimate goal of achieving safer and more efficient local, arterial and even nationwide traffic systems. This trend has indicated a new paradigm for the future intelligent transportation system. However, it will be challenging to accomplish this long-term goal with conventional control approaches because the transportation system, as many other infrastructures in our daily life, is a complex system of very large scale and high heterogeneity. There is an urgent need for advanced control solutions for the future fully connected transportation system. In this talk, the challenges and opportunities with respect to the control of fully connected transportation systems will be discussed. Both vehicle platooning control and transactive flow control will be introduced as illustrative examples.

**Prof. Enoch Yeung** is an Assistant Professor at the University of California Santa Barbara, a Visiting Faculty Scientist at PNNL, and a former staff member at PNNL. He holds a Ph.D. in Control and Dynamical Systems from the California Institute of Technology and a B.S. in Mathematics, magna cum laude, from Brigham Young University. He serves as the principal investigator for projects on distributed biological computing (HPDA), design of data-driven control architectures (PNNL's CCSI) and data-driven design and discovery for synthetic biological systems (DARPA SD2). He has led major research tasks on several multi-institutional, collaborative synthetic biological research programs including the Defense Advanced Research Projects Agency

(DARPA) Living Foundries program, the National Science Foundation (NSF) Molecular Programming Project, and the Air Force Office of Scientific Research's Biological Research Initiative. He has served on several advisory panels for DARPA, the National Institute of Standards and Technology, and the National Defense University. He is the recipient of the Kanel Foundation Fellowship, the NSF Graduate Fellowship, a National Defense Science and Engineering Fellowship, the PNNL Project Team of the Year Award, and the PNNL Outstanding Performance Award.

## Presentation:
## "Discovery and Characterization of Novel Feedback Control Mechanisms in Synthetic Gene Networks: From Principled Models to Deep Learning"

Biological control is ever present in our world, from the complex nanoscale interactions of microbial consortia to macro-scale social dynamics of ecosystems. Populations of millions of cells within a palm-sized test-tube implement stochastic and massively parallel control strategies, reprogramming their own DNA to manifest diverse control architectures over time. These control systems achieve power efficiency and robustness, at the nano to micro scale. To imbue such properties into novel control systems is the challenge of our time. In this talk Dr. Yeung will overview recent experimental and computational advances that accelerate design of novel control systems in the areas of synthetic biology and biomimetic computing. He will highlight two advances in particular: 1) the discovery of a novel biophysical mechanism for implementing feedback control in synthetic gene networks, and 2) the integration of deep learning and data-driven methods to generate a computational framework for predicting the operational envelopes of synthetic biocircuits. In the former, he will discuss how overlooked design properties of synthetic gene networks can be used to enforce local and fast feedback control, resulting in improved persistence (over 72 cell divisions) of memory in the genetic toggle switch. In the latter, he addresses the challenge of predicting biological system behavior over a range of conditions, given finite and noisy experimental samples. Specifically, he examines the problem of discovering models for moment dynamics of a biological network, as a function of small molecule control signals and temperature-based perturbations. He will introduce deep dynamic mode decomposition and show that the input-Koopman models learned from flow cytometry data predict biocircuit functionality with more than 90 percent accuracy over 1,000 experimental conditions.

**Prof. Subhonmesh Bose** is an Assistant Professor at the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. Prior to joining UIUC, he was an Atkinson Postdoctoral Fellow in Sustainability at Cornell University. He received his MS and Ph.D. at California Institute of Technology in Electrical Engineering in 2012 and 2014, respectively. And, he earned his B.Tech at the Indian Institute of Technology Kanpur.

He was a co-recipient of a best paper award in system operations and market economics in the IEEE Power and Energy Society General Meeting, 2013.

## Presentation:
## "Tie-line Scheduling in Electric Power Systems under Uncertainty"

Each system operator (SO) controls the grid assets over the power network within its own footprint (area). The tie-line scheduling problem seeks to optimize the power flows over tie-lines—the transmission lines that interconnect the grid in different areas. We leverage the theory of multi-parametric linear programming to propose algorithms for optimal tie-line scheduling with uncertain renewable supply. Our algorithms converge in finitely many iterations. And, the SOs of different areas are not required to reveal their dispatch cost structures, network constraints, or their uncertainty sets to arrive at the optimal tie-line schedule. We discuss the performance of the algorithms using several power system examples.

**Dr. Tom McDermott** is an IEEE Fellow who joined PNNL in August 2016 to provide technical leadership for the research portfolio in distribution analysis and automation, demand response, and distributed energy technologies. His primary research focus is on novel simulation, modeling and analysis capabilities.

## Presentation:
## "Distributed Controls for Electric Power Grid Modernization"

Dr. McDermott's talk will highlight the importance of distributed control methods that can balance the cost of communications and sensors, with objectives to improve efficiency, reliability, security and resilience of the electric power grid. Examples will be taken from the areas of smart inverters, protection, and transactive market structures.

**Dr. Henry Huang** (M'01 SM'05 F'17 IEEE) received his B. Eng. from Huazhong University of Science and Technology, Wuhan, China, and Ph.D. from Tsinghua University, Beijing, China, in 1994 and 1999, respectively. From 1998 to 2003, he conducted extensive research at the University of Hong Kong, McGill University (Canada), and the University of Alberta (Canada). He is currently a Laboratory Fellow and Technical Group Manager at PNNL. Dr. Huang has more than 140 peer-reviewed publications. His research interests include high performance computing, data analytics, and optimization and control for power systems and other related infrastructures. Dr. Huang is a Fellow of IEEE and active in several IEEE Power and Energy Society (PES) technical committees. He led the Richland Chapter to win the 2007 IEEE PES Outstanding Small Chapter Award. He received the 2008 PNNL Ronald L. Brodzinski Award for Early Career Exceptional Achievement and the 2009 IEEE PES

Outstanding Young Engineer Award. Dr. Huang is a registered Professional Engineer in Washington State.

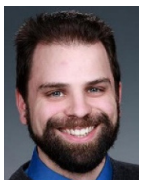
### Presentation: "High Performance Computing for Optimization and Control of Energy Systems"

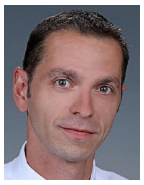
The increasing complexity and interdependency of energy systems pose significant challenges in controlling them for optimal performance. To tackle this challenge, high performance computing (HPC) is one of the important ingredients. Active participation of loads in the power grid vastly increases the possible number of control points. The wide-area nature of many critical systems requires signals to be transferred over long distance, leading to great dependency on communication networks. Resilience against disasters and threats require coordinated optimization and control of multiple critical infrastructures to achieve the goals of fast and effective emergency response and restoration. This talk will summarize these emerging issues and explore HPC's roles in the design and implementation of optimization and control for energy systems.

# Demonstrations

### Control Architecture to Support Large-scale Deployment of Wholesale-Retail Transactive Control Mechanism using the CCSI Test Bed

Transactive energy is a market-based control technique that has been proposed and studied over the past several years. This demonstration focuses on evaluating a PNNL-developed hierarchical control structure that incorporates transactive energy techniques to engage end-use load to participate in the wholesale real-time energy market. It highlights the ability of the architecture to integrate and control the inherent flexibility in loads in a stable manner while honoring customer preferences and realizing benefits for the system as a whole. In order to evaluate the proposed control system, CCSI has developed a test bed capability that supports simultaneous simulation of physical and virtual assets. This has been achieved by using the Framework for Network Co-Simulation (FNCS) to incorporate the simulated assets and the VOLTTRON™ technology to incorporate physical assets. The CCSI Test Bed facilitates exchange between transmission and distribution systems simulators, while allowing control algorithms to be implemented at each level of the hierarchical architecture. This demonstration aims to evaluate the performance of the proposed transactive energy control algorithm on a close-to-real-life power system scale model that incorporates tens of thousands of individually simulated distribution systems with millions of controllable loads. To alleviate the computational burden due to the simulation system complexity, the HPC resources at PNNL have been used.





**Presenters/Contributors**: Left to right, Jacob Hansen, Trevor Hardy, Priya Mana, Laurentiu Marinovici, Robert Lutes, Monish Mukherjee, and Tianzhixi (Tim) Yin.

## Test Bed Federation

This demonstration will highlight the CCSI federation tools project. It will feature a live connection between a partner site and a control system at PNNL. The demo will showcase both the ability to connect and control devices across our federation offerings. The demo will describe what federation is and the various ways to connect that were developed under this initiative.

**Presenter/Contributor**: Matt Engels and David Manz

## Multi-scale Incentive-Based Control of Distributed Assets

The DOE Advanced Research Projects Agency-Energy (ARPA-E) NODES project on Multi-scale Incentive-Based Control of Distributed Assets is led by PNNL, in partnership with United Technologies Research Center (UTRC), Southern California Edison and Spirae. One of the main objectives of the project, which is also the focus of this demonstration, is to test and validate the feasibility and performance of a novel hierarchical control strategy that coordinates the response of several different distributed energy resources to provide a range of ancillary grid services using a large scale grid co-simulation and hardware-in-the-loop platform.

**Presenters/Contributors**: Left to right, Karan Kalsi, Shwetha Niddodi, Veronica Adetola (UTRC) and Draguna Vrabie

## Facility Cybersecurity Framework (FCF) and Facility Cybersecurity Capability Maturity Model (F-C2M2)

This demonstration will provide insights into FCF and F-C2M2. PNNL and the DOE Office of Energy Efficiency & Renewable Energy's Federal Energy Management Program (FEMP) developed FCF to provide easy-to-follow general guidance, drawn from the National Institute of Standards and Technology (NIST) Cybersecurity Framework and a wide variety of industry best practices and guidance documents (i.e., NIST 800 series and DoD United Facilities Criteria). The FCF facilitates implementation of the May 2017 Presidential Executive Order (EO) on Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure, calls on federal agencies and critical infrastructure owners and operators to manage their cyber risk through adoption of NIST-Developed The Framework for Improving Critical Infrastructure Cybersecurity (EO 13636 & EO 13800).

F-C2M2 also belongs to the family of FEMP tools. F-C2M2 arises from a combination of existing cybersecurity standards, frameworks, programs, and initiatives. The F-C2M2 provides flexible guidance to help organizations develop and improve their cybersecurity capabilities. As a result, the F-C2M2 practices tend to be at a high level of abstraction, so that they can be interpreted for organizations of various structures and sizes. The F-C2M2 is organized into 10 domains. Each domain is a logical grouping of cybersecurity practices. The practices within a domain are grouped by objective—target achievements that support the domain. Within each objective, the practices are ordered by Maturity Indicator Level (MIL).

**Presenters/Contributors**: Left to right, Kate McMordie Stoughton, Michael Mylrea, Sri Nikhil Gourisetti, and Jey Castleberry (not pictured)

## Visual Analytics Supporting Reinforcement Learning in Control Systems

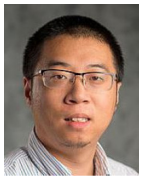
We will demonstrate a visual analytics system that supports a data scientist in building and evaluating reinforcement learning models for control systems. Reinforcement learning is more challenging than traditional, e.g., supervised, machine learning where a simple function mapping an input to an output is learned from a static set of examples. Instead, reinforcement models learn through trial and error by exploring their environment. To apply reinforcement learning to a problem, data scientists will conduct many "runs" across a broad sweep of model hyperparameters. Each run is a sequence of episodes, each episode is a sequence of states, actions, and reward, and states and actions can have arbitrary dimension. The model learns over time, both within and across episodes, creating non-trivial time dependencies in model behavior and performance. This

complexity can easily overwhelm the data scientist, making it difficult, without tool support, to answer simple questions about the outcome of an experiment, and what to try next. We address these issues with a visual analytics tool that allows the data scientist to understand the relationship between hyperparameters and model performance, understand patterns of behavior within and between runs, and explore the relationship between state, action, and reward. We demonstrate our tool with several control problems of varying difficulty from the OpenAI Gym, e.g, inverted pendulum, lunar lander, and walker.

**Presenters/Contributors**: Left to right, Dustin Arendt, Emily Saldanha, Todd Billow, Aritra Dasgupta, and Brenda Praggastis (not pictured)

## Transactive Controls on the PNNL Campus

The Clean Energy and Transactive Campus project (CETC), funded by DOE and the State of Washington, has produced methods and technologies to enable commercial building energy efficiency and transactive control of distributed energy resources. Specific areas of capability development include Intelligent Load Control (ILC) for buildings; Transactive Control and Coordination of Building Energy Loads (TCC); Passive and Active Diagnostics; and Integration of Distributed Renewable Energy Resources. CETC continues to gain recognition for its innovations. This demonstration will highlight ILC and TCC applications.



**Presenters/Contributors**: Left to right, Robert Lutes, Sen Huang, Hung Ngo and Srinivas Katipamula

## Pink Elephant Unicorn: ICS Security Assessment

This demonstration will provide a simple example of how cyber professionals conduct a security assessment of a network involving control systems. This set of challenges was part of Pink Elephant Unicorn 5, PNNL's semi-annual cyber security competition for all skill levels, where participants were given a series of challenges such as:

- Perform network reconnaissance and analyze using common cyber tools
- Explore the vulnerabilities in the MODBUS protocol
- Experience and manipulate ICS protocols like MODBUS
- Examine the basic elements of a Man-in-the-middle attack.

**Presenter**: Daniel Sanner

# Posters

## Large-Scale Cyber-Physical Networks: Understanding Couplings and Decompositions

Distributed analysis and control relies on the separability of large networks into weakly interacting subsystems, permitting only minimal information exchange between subsystems. Decomposition of nonlinear networks into weakly interacting subsystems requires understanding the nature of coupling and interaction strengths in a dynamical network. We introduce a notion of generalized power and energy-flow in dynamical networks applying the theory of vector Lyapunov functions. Moreover, we develop an algorithm, based on sum-of-squares programming, to estimate the energy-flows across polynomial networks via a comparison systems analysis. Energy-flows vary as per the initial conditions, allowing dynamic partitioning of the networks.

**Presenter/Contributors**: Left to right, Soumya Kundu, Abdullah Al Maruf (WSU), and Enoch Yeung (UCSB)

## HVAC-Controls Functional Performance Test

Automated functional testing methods for building Heating, Ventilation, and Air Conditioning (HVAC) systems is a quality assurance process that manipulates inputs and examines outputs to enable understanding of what the system does. The testing procedures can detect operational faults in HVAC systems and help save energy, reduce maintenance costs and improve comfort. Functional testing is being performed on a multi-zone variable-air-volume HVAC system at a PNNL campus building for informing future experiments on controller and actuator responses, and HVAC system dynamics.

**Presenter/Contributors**: Left to right, Nikitha Radhakrishnan, Paul Ehrlich, and Mark Rice

## Research on Transportation Systems at PNNL: Traffic Flow and Powertrain Controls

This poster highlights work the U.S. Department of Energy has funded that's focused on smart-mobility and vehicle level control. PNNL and multiple partners are involved. The smart-mobility effort seeks to develop stochastic distribution control for intersection signal timing, so as to achieve a uniform distribution of traffic flows over an urban area, as well as to minimize energy consumption. The vehicle control activities are pursuing co-optimization of powertrain and aftertreatment systems using V2V and V2I info, to achieve significant fuel savings.

**Presenter/Contributors**: Wanshi Hong, Hong Wang, Indrasis Chakraborty, and Jianming Lian

## Contact

Michael Brambley
Pacific Northwest National Laboratory
P.O. Box 999, MSIN J5-15
Richland, WA 99354
Michael.Brambley@pnnl.gov
(509) 375-6875

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