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Control of Complex Systems Initiative

NEWSLETTER



Control of Complex Systems Initiative



The Control of Complex Systems Initiative is a Pacific Northwest National Laboratory investment to build advanced controls capabilities for large-scale, complex infrastructures, particularly the power grid, buildings and buildings-grid integration. The five-year initiative was launched in fiscal year 2014.

CCSI Leadership

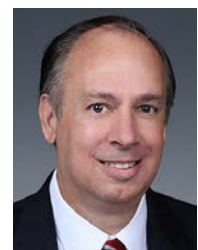
Initiative Lead: [Michael Brambley](#)
Co-Lead/Chief Scientist:
Hong Wang
Theory Lead: Dragana Vrabie
Tools Lead: Thomas Edgar
Test Bed Co-Leads: Mark Rice,
Paul Ehrlich
Demonstrations Lead: Jason Fuller
Outreach Lead: Karan Kalsi

October 2017

Mike's Perspective

Michael Brambley, Initiative Lead

The Control of Complex Systems Initiative completed its fourth year at the end of September, and 12 months remain to wrap up our existing projects, meet our overarching objective to establish a new set of control capabilities at PNNL and continue transitioning CCSI-developed tools and the test bed for use by the broader control community.



As an introduction to this issue of the CCSI Newsletter, I want to take a moment to briefly recap some of the initiative's accomplishments over the past fiscal year, several of which you'll read more about in this newsletter.

- Our annual workshop, held in conjunction with the American Control Conference in Seattle in May, attracted national and international experts sharing the latest advances in control for modernization of the electric power grid
- We launched the Control of Complex Systems Lecture Series in February, featuring Dr. Richard Murray of Caltech as our inaugural speaker
- Arion, CCSI's high-level modeling language and library, became available as open source software for download on PNNL's [GitHub](#) site

Project Coordinator:
Sherry Kowalski
Transition Lead: Jennifer Lee
Communications: Tim Ledbetter
[Contact CCSI](#)

Project Helps Land DARPA Work

A multi-year robust design project is coming to PNNL, due in part to research conducted in CCSI. The Defense Advanced Research Projects Agency's Information Innovation Office (I2O) recently announced the award for "Learning Deep Koopman Operators for Data-Driven Model Discovery of Synthetic Biological Systems."

The project begins in fiscal year (FY) 2018, runs through FY 2021 and will be led by Enoch Yeung. DARPA awarded \$660,000 per year. Yeung also leads the CCSI project, "Control Framework for Large-Scale Complex Systems."



Enoch Yeung

"We leveraged ideas from our CCSI work to help win the DARPA award," Yeung explained. "The ideas were related to extended dynamic mode decomposition algorithms for learning Koopman operators, and generalizations of those

- We built upon and extended the capabilities of two PNNL-developed software programs, VOLTRON™ and the Framework for Network Co-Simulation (FNCS), creating new resources for control method/system testing and deployment
- In the theory area, CCSI projects developed theoretical guarantees and computationally scalable algorithms for verification of robust equilibria in infrastructure networks, developed analysis and synthesis methods to systematically architect and design control hierarchies, and explored opportunities at the intersection of control and machine learning
- We continued work on the CCSI test bed, beginning implementation of federation with test facilities at two other organizations
- CCSI staff published papers in notable refereed journals, presented their research in prominent conferences and at other events, and provided leadership to a wide range of professional societies
- The CCSI website went live this summer, providing us with a mechanism to more broadly communicate initiative information.

This is just a sampling of our accomplishments. We look forward to the challenge of the coming year and will keep you posted on our progress. Please contact me at my e-mail address below if you desire more detailed discussions on any of the content in this newsletter. You can also reach out to us via the "Contact CCSI" link in the informational box at left.

Best regards,

Mike

Michael.Brambley@pnnl.gov

CCSI Online Initiative Launches Website

The Control of Complex Systems Initiative's [website](#) is live.

The website is part of an effort to further build awareness of CCSI with the broader national and international controls community.

approaches leveraging deep learning. Another factor was our work in prediction error methods for benchmarking Koopman operator fidelity."

The CCSI project is part of the initiative's Theory Focus Area led by Draguna Vrabie. "It is exciting to see how complex systems control challenges, coupled with research prowess and fresh thinking, positioned Enoch's team for success in support of the DARPA I2O mission," Vrabie said. "This outcome fuels our commitment to further build PNNL's capability in dynamical systems and control theory."

GE's McDonald Speaks at Lecture Series Event

On September 7 at PNNL, the Control of Complex Systems Lecture Series featured John D. McDonald, Smart Grid Business Development leader for GE Grid Solutions. The lecture series is sponsored by CCSI.

McDonald spoke on, "Grid Modernization - Technological Advancements Beyond Smart Grid." He discussed key industry and societal trends impacting U.S. energy system development and progress, as well as grid needs, such as broader, holistic thinking and solutions, that must be addressed for the future.

The site includes overviews of CCSI and its research projects, and also features info about the initiative's publications, leadership, lecture series, annual workshops, and integrated demonstrations.

The site's URL is <http://controls.pnnl.gov/>.



The screenshot shows the CCSI website homepage. At the top, there is the Pacific Northwest National Laboratory logo and the U.S. Department of Energy logo. Below the logos is a navigation menu with links for Home, Research, Publications, Jobs, Newsroom, and Contacts. The main heading is "Control of Complex Systems Initiative". Below this, there is a navigation menu with links for Home, Research, Annual Workshop, Integrated Demonstration, Lecture Series, Team Members, Publications, and Contacts. The main content area includes a description of the initiative, its goals, and a list of planned outcomes.

CCSI's website, which went live in July, features a variety of information about the initiative and its projects.

Kalsi Selected for Caltech Appointment

Karan Kalsi, CCSI's Outreach lead, will serve as a Visiting Associate at the California Institute of Technology (Caltech) in Pasadena. The year-long appointment began September 1 and is the latest in a growing number of collaborative activities between PNNL and Caltech.



Karan Kalsi

"I'm looking forward to partnering with Caltech staff to work on control theory for large-scale complex systems," Kalsi said. His appointment also will include a leadership role in developing proposals for funding opportunities from the Department of Energy and other federal agencies.

Over the course of the year, Kalsi will make periodic visits to the Caltech campus, where he'll work in Computing and Mathematical Sciences, which is within Caltech's Division of

The lecture series is designed to bring recognized experts in control to PNNL to share insights into the latest advances in the field.

Mr. McDonald is an award-winning industry leader, technical expert, educator, and speaker. He possesses more than four decades of experience in the electric utility industry, and has provided leadership to numerous national professional and academic societies and committees.

[View John McDonald's lecture.](#)



John McDonald spoke about the technology, policy and customer needs of a smarter power grid.



McDonald's visit to PNNL included a tour of the Electricity Infrastructure Operations Center and, above, the Visualization and Interaction Studio. In the studio, assisted by PNNL's Russ Burtner, he tried out technologies that allow users to realistically experience distant environments and

Engineering and Applied Science. His host at Caltech is Dr. Richard Murray, who serves on CCSI's Advisory Committee.

Kalsi is a staff engineer in PNNL's Optimization and Controls Group, the principal investigator of several large DOE projects, and has served in CCSI leadership roles since the initiative's inception.

Spotlight on CCSI Staff Researcher Enjoys Applying Expertise to Controls

Priya Thekkumparambath Mana joined Pacific Northwest National Laboratory as an intern in 2016 and was hired to a Staff Engineer position in early 2017. Priya has been involved in two CCSI projects: Integrated Control Testing Under Complexity, and Co-Simulation Platform for Rapid Prototyping of Control Algorithms (which was recently completed). In the following interview, Priya talks about her work with CCSI, research interests and life outside of work.



Question: You have a relatively long last name...

Priya: Yes! But if you sound it out syllable by syllable, it's not as difficult to pronounce as it looks. I can also be addressed as Priya TM.

Question: Tell us about your background, and how you came to PNNL.

Priya: I grew up in India and earned my bachelor's degree there, in Electronics and Instrumentation. I worked in the software industry for a brief period prior to coming here to the Tri-Cities area. I started working toward my Master's degree at Washington State University. One of my professors introduced me to PNNL's work in the grid and controls area. I became an intern, with Jason Fuller (CCSI Demonstrations Lead) as my mentor, and got a lot of exposure to grid and controls work, what people are doing here, and I liked it. I started working on CCSI projects, and started reading the publications. I had taken control courses, so I found the work to be interesting.

locations, which can facilitate training and other applications.

Lecture Series Video with R. Murray Now Available

A video of Richard Murray's February 21 Control of Complex Systems

Lecture Series presentation is now available on [PNNL's YouTube channel](#).



Dr. Murray presented, "Specification and Synthesis of Complex, Networked Control Systems with Applications in Physical, Biological and Computational Sciences."

CCSI's Third Workshop Features National and International Experts

Approximately 50 experts in control, optimization, economics and power systems gathered for CCSI's third annual workshop, "Control of Complex Systems: An Integrated Perspective on Modern Power Grid Control." The workshop was held May 22-23, in conjunction with the

Question: You work in several disciplines at PNNL, correct?

Priya: At this point I work mostly in grid, but along with that there's the control activities and some software programming. I'm at a nice juncture of three areas that are of interest to me and I want to continue growing in my knowledge.

Question: You participated as a presenter in this year's CCSI Integrated Demonstration, which is held in conjunction with the initiative's Annual Review and conveys how CCSI-developed tools work together to solve problems. Describe that experience.

Priya: This was my first time as a presenter for an external review at PNNL. Jacob Hansen (principal investigator) and I shared with the audience our work in distributed control methods from CCSI's Theory Area, and with help from our colleague Trevor Hardy, modeled a framework to test such algorithms using the co-simulation capabilities developed under CCSI. Through this work, we could gain an understanding of how control algorithms would behave in more realistic and complex scenarios. The presentation went well, and one of the nice outcomes was the positive response we received. Other PNNL staff and CCSI Advisory Committee members talked with us about possibilities, the ways in which our methods can be developed and applied. I had good conversations with many people. It was great to be able to share our information with others from across PNNL and externally, and to see where our work will go from here.

Question: What do you do in your spare time?

Priya: I enjoy hiking and backpacking with my husband and two dogs. I also participate in karate, practicing regularly. Living in the Tri-Cities means we have less traffic and more time to do the things we enjoy.

American Control Conference (ACC) in Seattle.

"The workshop speakers provided some of the latest thinking in the control field, which will help sharpen CCSI's focus as we enter our final year as an initiative and begin transitioning the capabilities we've developed for broader use," said CCSI Lead Michael Brambley. He added the connection with ACC provided some unique opportunities to interact with leaders in control and raise CCSI visibility.

The participants represented more than 20 national and international institutions and companies. Sonja Glavaski, program director for the DOE Advanced Research Projects Agency-Energy, keynoted the event. Other speakers included representatives from industry, research and academia.

The [workshop](#) focused on three technical areas: Dynamics and Control; Analytics and Optimization; and Economics and Market Design. The event also included an industry perspectives session and a round of short "lightning talks" by nine PNNL researchers.



Priya talks with colleague Trevor Hardy in PNNL's Building Operations Control Center.

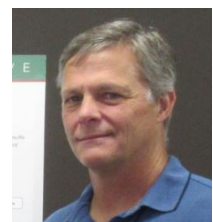
Project Highlight

Researchers Address Uncertainty in Complex Systems

CCSI researchers are putting final touches on a toolkit that can estimate uncertainties, improving the design and operation of complex systems.

The toolkit, which can be used in the MATLAB language and interactive environment, is one of the outcomes of the CCSI project, "Scalable Hierarchical Validation and Calibration for Robust Distributed Control of Large-Scale Complex Systems under Uncertainty," led by Dave Engel. The project completed its third and final year at the end of September.

"Optimal, efficient control of the nation's complex systems--such as the power grid, buildings, and transportation--requires a strong predictive capability that enables operators to see into the future and efficiently manage the system to meet user needs," Engel explained. This capability is hindered by uncertainties, or factors not readily evident, that impact prediction and, ultimately, system operations. Being able to quantify uncertainties informs development of more sophisticated models and simulations,



Dave Engel



ARPA-E's Dr. Sonja Glavaski keynoted the workshop.



Professor Colin Jones of École polytechnique fédérale de Lausanne speaks on "Predictive Dispatch and Demand Response for Commercial Buildings."



PNNL's Soumya Kundu presents his research in the "lightning talks" portion of the workshop.



leading to better system designs and robust control decisions.

CCSI researchers applied ensemble-based methods such as Kalman Filter, Bayesian and Monte Carlo to examine and address a range of uncertainty questions. The researchers went on to test their ideas in two demonstration problems. The first demonstration focused on application of CCSI-developed approaches to the coordination of a group of 1,000 thermostats, examining uncertainty effects on prediction and the control of the total power. The second demonstration looked at application of uncertainty quantification to the optimal scheduling of a population of water heaters, where the temperature changes and energy consumption need to be predicted with simulations.

CCSI research and results from the demonstrations informed the development of a general framework and toolkit for uncertainty quantification, optimization, and model calibration and validation. This systematic treatment of the uncertainties involved in the control of complex systems can be applied by a wide range of users to estimate uncertainties while performing modeling tasks.

"As one of the final steps, we'll be developing a user guide for the toolkit," Engel noted. A journal paper on the project's work, "Ensemble-Based Uncertainty Quantification for Coordination and Control of Thermostatically Controlled Loads," was recently published online by the Journal of Control and Decision.

Initiative's Annual Review Held in July; Advisory Committee Pleased with Progress

Following CCSI's Annual Review July 6-7 at PNNL, the initiative's Advisory Committee concluded CCSI is on track to meet its objectives and applauded researchers and the quality of research that has been achieved. The committee also challenged the initiative team to press forward on development and completion of a federated test bed, which would bring together CCSI with industry and academia partners and establish a signature control capability at PNNL.

The workshop provided ample networking opportunities.

Photos by Haoxiang Yang

Recent CCSI Publications

Journal Papers

Dvijotham, K., E. Malada and J.W. Simpson-Porco. "High-Voltage Solution in Radial Power Networks: Existence, Properties, and Equivalent Algorithms." *IEEE Control Systems Letters* 1(2):322-327. DOI: [10.1109/LCSYS.2017.2717578](https://doi.org/10.1109/LCSYS.2017.2717578).

Wu, D., J. Lian, Y. Sun, T. Yang and J. Hansen, "Hierarchical Control Framework for Integrated Coordination between Distributed Energy Resources and Demand Response." *Electric Power Systems Research* 150:45-54. DOI: [10.1016/j.epsr.2017.05.002](https://doi.org/10.1016/j.epsr.2017.05.002).

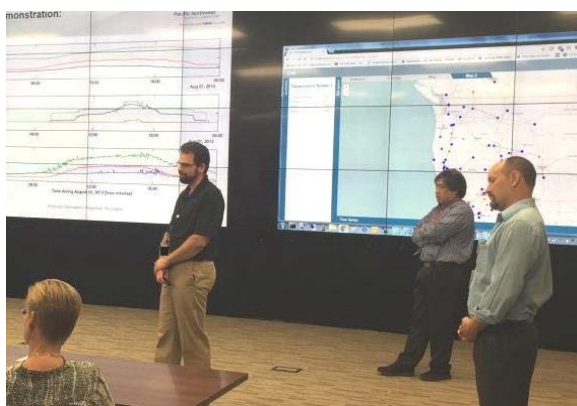
Wu, J., T. Yang, D. Wu, K. Kalsi and K. H. Johansson, "Distributed Optimal Dispatch of Distributed Energy Resources over Lossy Communication Networks." *IEEE Transactions on Smart Grid* 8(6): 3125-3137. DOI: [10.1109/TSG.2017.2720761](https://doi.org/10.1109/TSG.2017.2720761).

Yang, T., J. Lu, D. Wu, J. Wu, G. Shi, Z. Meng, and K.H. Johansson. "A Distributed Algorithm for Economic Dispatch over Time-Varying Directed Networks with Delays." *IEEE Transactions on Industrial Electronics* 64(6):5095-5106. DOI: [10.1109/TIE.2016.2617832](https://doi.org/10.1109/TIE.2016.2617832).

Zhang, Q.C., J.L. Zhou, H. Wang and T.Y. Chai. "Output Feedback Stabilization for a Class of Multi-

The review included updates on CCSI activities and progress, an integrated demonstration that showed how CCSI-developed tools work together to achieve control solutions, and a poster session that allowed initiative researchers to showcase their projects.

Advisory committee participants included Alexis Abramson (chair), Case Western Reserve University; Magnus Egerstedt, Georgia Institute of Technology; Richard Murray, California Institute of Technology; Rob Pratt, PNNL; Dennis Stiles (secretary), PNNL; and Claire Tomlin, University of California-Berkeley. Committee member Ralph Kappelhoff of GE Energy Connections was unable to participate because of a business conflict.



During one of the Annual Review's integrated demos, research staff members (standing, from left to right) Trevor Hardy, George Chin and Jason Fuller field questions from the Advisory Committee.



This year's Annual Review poster session went all electronic, with posters displayed on screens in the Electricity Infrastructure Operations Center in PNNL's Systems Engineering Building.

variable Bilinear Stochastic Systems with Stochastic Coupling Attenuation." *IEEE Transactions on Automatic Control* 62:2936-2942. DOI:[10.1109/TAC.2016.2604683](https://doi.org/10.1109/TAC.2016.2604683).

Zhou, P., Y. Lv, H. Wang, and T.Y. Chai. "Data-Driven Robust RVFLNs Modeling of Blast Furnace Ironmaking Process Using Cauchy Distribution Weighted M-Estimation." *IEEE Transactions on Industrial Electronics* 64(9):7141-7151. DOI: [10.1109/TIE.2017.2686369](https://doi.org/10.1109/TIE.2017.2686369).

Li, W., J. Lian, D. Engel and H. Wang. "Ensemble-based Uncertainty Quantification for Coordination and Control of Thermostatically Controlled Loads." *Journal of Control and Decision*. (In press). DOI: [10.1080/23307706.2017.1353931](https://doi.org/10.1080/23307706.2017.1353931).

Zhang, Y., T.Chai, H. Wang, D. Wang and X. Chen. "Nonlinear Decoupling Control with ANFIS-based Unmodeled Dynamics Compensation for a Class of Complex Industrial Processes." *IEEE Transactions on Neural Networks and Learning Systems*. (Published online; in press). DOI: [10.1109/TNNLS.2017.2691905](https://doi.org/10.1109/TNNLS.2017.2691905).

Zhou, Y., Q. Zhang, H. Wang, P. Zhou and T. Chai. "EKF-Based Enhanced Performance Controller Design for Nonlinear Stochastic Systems." *IEEE Transactions on Automatic Control*. (Published online; in press). DOI: [10.1109/TAC.2017.2742661](https://doi.org/10.1109/TAC.2017.2742661).

Conference Paper

J. Hansen, T.W. Edgar, J.A. Daily and D. Wu. 2017. "Evaluating Transactive Controls of Integrated Transmission and Distribution

Tomlin and Stiles Join Advisory Committee

Claire Tomlin of the University of California-Berkeley and Dennis Stiles of PNNL are recent additions to the CCSI Advisory Committee, while two others, Magnus Egerstedt and Paul Ehrlich, have stepped down from their roles.

Tomlin is a Professor of Electrical Engineering and Computer Sciences at UC-Berkeley, where she holds the Charles A. Desoer Chair in Engineering. Stiles is PNNL's acting Energy Efficiency and Renewable Energy market sector manager. He also manages two PNNL sub-sectors, Building Technologies and Energy Efficiency.

Egerstedt, of the Georgia Institute of Technology, recently asked to leave the committee due to responsibilities in his new role as Executive Director of the Institute for Robotics and Intelligent Machines at Georgia Tech. Ehrlich was serving as an internal PNNL representative on the committee, but is now working on the initiative itself, becoming co-lead of CCSI's Test Bed Focus Area and principal investigator of the Campus as a Laboratory project.

"We're disappointed that Magnus and Paul, two long-serving members, won't be continuing on the committee, but we're extremely grateful for their many contributions to CCSI,"

said Mike Brambley, Initiative Lead. He added, "We're pleased to have Claire and Dennis onboard, and are looking forward to benefiting from their perspectives and working with them to shape CCSI, as the Advisory Committee plays a crucial role in guiding the initiative."

CCSI's Wang Speaks at Singapore Smart Grid Conference

CCSI Co-Lead and Chief Scientist Hong Wang gave the keynote presentation at the 1st International Conference on Smart Grid Technology in Singapore on September 11. The keynote was titled, "Solving Stochastic Optimization by Shaping the Probability Density Function of Cost Functions and Constraint Equations."

Systems using the Framework for Network Co-Simulation." *American Control Conference*, Seattle, WA.

PNNL-SA-130132



As part of the trip, Wang visited the National University of Singapore's Cybersecurity Laboratory.

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FEEDBACK?

STAY CONNECTED:    