Annual Report for Period: 10/2011 - 09/2012
Submitted on: 08/13/2012
Principal Investigator: Lemmon, Michael D.
Award ID: 0925229
Organization: University of Notre Dame
Submitted By:
Lemmon, Michael - Principal Investigator
Title:
Distributed Optimization, Estimation, and Control of Networked Systems through Event-triggered Message Passing

Project Participants

Senior Personnel

Name: Lemmon, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Wan, Pu
Worked for more than 160 Hours: Yes
Contribution to Project:
Pu Wan finished up his Ph.D. work under this project. His work consisted of developing event-triggered optimization schemes for network utility maximization problems and economic dispatch problems in microgrids.

Name: Li, Lichun
Worked for more than 160 Hours: Yes
Contribution to Project:
Lichun Li work focuses on event-triggered estimation and control where an explicit constraint exists on the transmission bandwidth.

Name: Hu, Bin
Worked for more than 160 Hours: Yes
Contribution to Project:
Bin Hu is studying event-triggered receding horizon control

Name: Wang, Zhao
Worked for more than 160 Hours: Yes
Contribution to Project:
This person is studying reactive control of weak distribution feeders in power networks. One approach to this control involves the use of event-triggered dispatching of reactive power.

Name: Tamba, Tua
Worked for more than 160 Hours: Yes
Contribution to Project:
This person is studying the use of model checking methods on field data to detect the likelihood of regime shifts in aquatic ecosystems.

Name: Yi, Zonggen
Worked for more than 160 Hours: Yes
Contribution to Project:
first year graduate student working on event-triggered control

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

EmNet LLC

EmNet LLC builds and deploys wireless sensor-actuator networks that are designed to operate in harsh environments for extended periods (2-3 years) of time. This company has provided wireless networking equipment used in their wireless sensor-actuator networks as well as details regrading their current customers applications.

Odyssian Technology

Odyssian Technology is a small business that is developing distributed wireless controllers for electrical microgrids. Odyssian is providing financial support to the PI with regard to a supervisory power dispatch controller for these small power systems. The system is implemented over a wireless communication network. The PI is providing technical assistance with regard to wireless communication and power dispatch control algorithms.

Other Collaborators or Contacts

As part of this project we've had contacts with European researchers Petru Eles (Linkoping), A. Cervin (Lund), Mikael Johansson (KTH), Kalle Johansson (KTH), Alberto Bemporad (Univ Trento) and Maurice Heemels (Eindhoven). These contact arose from a chapter on event-triggered systems in a Springer book on Network Control Systems that should appear in late 2010.

We've also had contact with U.S. research scientists in the power systems community, R. Lasseter (U. Wisconsin - Madison) and P. Krein, A. Dominiguez-Garcia, and P. Chapman (UIUC). These contacts arose from participation in a phase 2 STTR on a hierarchical control architecture for microgrids.

Activities and Findings

Research and Education Activities:

Project participants attended and presented papers at the following conferences and workshops

1) IEEE Conference on Decision and Control, Shanghai, China, December 2009
2) American Control Conference, Baltimore, MD, July 2010.
3) IEEE Conference on Decision and Control, Atlanta, GA, Dec. 2010.
4) Hybrid Systems: computation and control, Chicago, IL, April 2011.
5) IEEE Conference on Decision and Control, Orlando Florida, December 2011
6) Allerton 2011 Workshop, University of Illinois Urbana-Champaign, 2011
7) IFAC Conference on Analysis and Design of Hybrid Systems, Eindhoven, Netherlands, June 2012
8) Hybrid Systems: computation and control, Beijing, China, April 2012

The following conference papers were presented

1) [Li10] Lichun Li and M.D. Lemmon, Event-triggered output feedback control of finite horizon discrete-time multi-dimensional linear processes, Proceedings of IEEE Conference on Decision and Control, Atlanta, Georgia, December 2010.

2) [Li10a] L. Li, M.D. Lemmon and X. Wang, Event-Triggered State Estimation in Vector Linear Processes, American Control Conference, Baltimore, USA, 2010.
3) [Wan10] P. Wan and M.D. Lemmon, Optimal power flow in microgrids using event-triggered optimization, American Control Conference, Baltimore, USA, 2010
4) [Wang10] X. Wang and M.D. Lemmon, Asymptotic stability in distributed event-triggered networked control systems with delays, American Control Conference, Baltimore, USA, 2010
5) [Wang11] X. Wang and M.D. Lemmon (2011), Minimum Attention Controllers for Event-triggered Feedback Systems, IEEE Conference on Decision and Control, Orlando Florida, December 2011.
6) [Li11] L. Li and M.D. Lemmon (2011), Performance and average sampling period of sub-optimal triggering event in event triggered state estimation, IEEE Conference on Decision and Control, Orlando Florida, December 2011
7) [Li11a] L. Li and M.D. Lemmon (2011), Weakly coupled event-triggered output feedback system in wireless networked contorl systms, Allerton 2011 Workshop, University of Illinois Urbana Champaign
8) [Li12] Lichun Li, Bin Hu, and M.D. Lemmon (2012), Resilient Event-triggered systems with limited communication, IEEE Conference on Decision and Control, Hawaii, USA, December 2012
9) [Li12a] Lichun Li, X. Wang and M.D. Lemmon (2012), Stabilizing bit rates for perturbed event-triggered control systems, IFAC Conference on Analysis and Design of Hybrid Systems, Eindhoven, Netherlands, June 2012.
10) [Li12b] Lichun Li, M.D. Lemmon and X. Wang (2012), Stabilziing Bit-rates in Quantized Event-triggered control systems, Hybrid Systems: computation and control, Beijing, China, April 2012.

The following journal papers have appeared:
1) X. Wang and M.D. Lemmon, Self-triggering under state-independent disturbances, IEEE Transactions on Automatic Control, volume 55, no. 6, pages 1494-1500, 2010.

2) X. Wang and M.D. Lemmon (2011), Event-triggering in distributed networked control systems, IEEE Transactions on Automatic Control, Volume 56, number 3, pages 586-601, March 2011.

3) X. Wang and M.D. Lemmon (2012), On Event Design in Event-Triggered Feedback Systems, Automatica, volume 47, number 10, pages 2319-2322, 2012.

The following journal papers have been submitted for publication
1)Lichun Li, M.D. Lemmon, Weakly coupled transmissins in event-triggered output feedback systems, submitted to Journal on Discrete Event Dynamical Systems, May 2012.

Dr. Lemmon helped organize an invited session on cyber-physical systems in the 2009 IEEE conference on decision and control (CDC) Shanghai, China.

Dr. Lemmon served on the program committee for the 2010 real-time and embedded technology and applications symposium (RTAS 2010).

Dr. Lemmon served on the program committee for the 2010 hybrid systems computation and control workshop (HSCC 2010).

Dr. Lemmon began working on a phase 2 STTR project developing a hierarchical control architecture for microgrids. The event-triggering methods being developed in this project were used as part of a power dispatcher (findings published in 2010 ACC). In 2011, Dr. Lemmon began working under the sponsorship of GE Energy to apply these ideas to the integration of LV microgrids in MV distribution feeders.

Dr. Lemmon (January 2010) completed a book chapter on event-triggered control for a

Springer book on Networked Control Systems that appeared in 2010.

Dr. Lemmon (Spring semester 2010 and 2011) developed course on cyber-physical systems that focuses on modeling, verification, and control verification. One chapter in these lecture notes deals with event-triggered feedback systems.

Dr. Lemmon was invited to present at the Workshop on Control of Computing Systems, December 5-7, 2011, organized by the Linnaeus excellence center LCCC (www.lccc.lth.se) at Lund University, Sweden

Findings:

This project began studying event-triggered estimation with hard bandwidth constraints on the feedback channel. Our work approached this problem as an optimal control problem that sought to choose event triggers that minimize mean square estimation error subject to a limit on the number of transmissions over a fixed window. Related work was done by Imer and Basar for scalar systems, but the computational complexity of the approach made it impractical to compute event-thresholds for multi-dimensional systems. Our work established a sub-optimal approximation for computing event-triggers that is polynomial in state dimension. While this approach is suboptimal, experiments indicate that the resulting thresholds closely approximate the optimal ones (Li/Lemmon, ACC 2010, CDC 2011). Another finding over this period was that this approach could also be applied to event-triggered output feedback controllers (Li/Lemmon CDC 2010). One problem with event-triggered output feedback control is that event transmission from sensor-to-controller and controller-to-actuator can be tightly synchronized. A method for reducing the coupling between these events was reported in (Li/Lemmon Allerton 2011). These methods also made use of the sub-optimal approximations employed in event-triggered estimation. The polynomial complexity for computing these event triggers allows us to develop event-triggered output feedback controllers for multi-dimensional systems. In particular, we've implemented such a controller for a nonlinear 3DOF helicopter system. A video (see project's website) for this system shows that it has good performance with greatly reduced CPU utilization.

Early work with L2 event-triggered systems assumed that plant disturbances were bounded by a class K function of the state. This requirement was relaxed to state-independent disturbances by imposing a minimum sampling time condition on the system. The resulting event-triggered system was still shown to be L2 stable in a recent journal publication (Wang/Lemmon, IEEE Transactions Automatic Control, Vol 55, pp 1494, June 2010).

This project recently published a paper discussing the design of event-triggers that maximize the time between triggering events (Automatica 2011).

An important use of event-triggered control was reported in [Wang/Lemmon, IEEE Transactions Automatic Control, Vol 56, pp 586, March 2011]. This paper describes the use of event-triggered signalling in distributed networked control systems. A key innovation in this work is its use of a 'push' paradigm for network communication, where information is 'pushed' to neighbors based on their anticipated need for that information. This work is significant because it is one of the first papers showing how to implement robust event-triggered signalling in distributed networked control systems.

Early work with event-triggered optimization had demonstrated that the approach could greatly reduce the message passing used in certain network utility maximization problems. This project has found that these methods could also be used to build distributed algorithms that optimize real power dispatch in power grids. simPower simulations of the resulting systems demonstrate good performance with greatly reduced frequency of message passing.

The approach seems to provide a secure and cost-effective manner of distributing power dispatch in power generation/distribution systems (Wan/Lemmon, ACC2010, microgrid paper).

Recent work [Li12a,Li12b] has examined the impact dynamically quantized measurements have on event-triggered systems. This work has identified practical upper and lower bounds on the bit-rate needed to achieve input-to-state stability in nonlinear event-triggered control systems. One of the remarkable findings of this work is that in the absence of disturbances, it is possible to design controllers and quantization maps whose bit-rate asymptotically go to zero as the system approaches its equilibrium. In the presence of noise, these bit rates monotonically decrease to a steady state level consistent with the well-known necessary/sufficient bit-rate bounds for stabilizing controls. With these findings it was then possible to re-examine the notion of 'resilience' in feedback control systems [Li12].

One of the weaknesses in the earlier work concerning optimal event-triggered feedback [Li10, Li10a, Li11, Li11a] was the complexity associated with determining the optimal triggering set. Current work has shown that it is possible to more easily compute these triggering sets using the SOS toolkit. The manuscript describing these results is currently under preparation.

Training and Development:

Through interactions with Odyssian LLC this project has provided students with a practical real-life platform upon which to base their theoretical work. One student (P. Wan) developed simPower simulations of Univ of Wisconsin's microgrid testbed as part of his Ph.D. dissertation work. That simulation used the power dispatch problem in microgrids as a practical application of Mr. Wan's work on event-triggered optimization. Another student, Zhao Wang, has been using this simulation to develop methods for controlling reactive power in weak distribution feeders. In 2011/2012, Mr. Wang has been using these simulations to develop novel methods for reactive power control of MV distribution feeders. His proposed approach involves the use of low-voltage microgrids to provide reactive power support. One of the chief technical issues in this method concerns the weakness in the LV microgrid. Recent results (in preparation) have developed a passivity based method for assessing the transient stability of such microgrids.

Outreach Activities:

Project outreach activities have revolved around interactions with Notre Dame's biology department. The PI has served as a resource to ND's ecological scientists regarding wireless sensor network technology by providing technical expertise and connecting ecological scientists to local sensor network businesses (EmNet LLC and Scientific Methods Inc). This outreach helped ND's biology department to obtain a $10 million grant to establish an Environmental Change Initiative (ND-ECI) studying the impact that global climate change has on natural and man-made environments. More recently, a student (Tua Tamba) has been partially funded from this project to use robust model checking with field data to detect the likelihood of regime shifts in aquatic ecosystems.

The project's efforts with distributed control of power systems has led to outreach efforts with Notre Dame's 'Center for Global Development'. In particular, this project has provided technical support to a recently awarded project (Accenture Fund) that is installing microgrids in Uganda.

Journal Publications

X. Wang and M.D. Lemmon, "Event-triggering in distributed networked control systems", IEEE Transactions on Automatic Control, p. 586, vol. 56, (2011). Published, 10.1109/TAC.2010.2057951

X. Wang and M.D. Lemmon, "Self-triggering under state-independent disturbances", IEEE Transactions on Automatic Control, p. 1494, vol. 55, (2010). Published, 10.1109/TAC.2010.2045697

X. Wang and M.D. Lemmon, "On event design in event-triggered feedback systems", Automatica, p. 23, vol. 47, (2011). Published, 10.1016

Lichun Li and M.D. Lemmon, "Weakly coupled transmissions in Event Triggered Output Feedback Systems", Journal on Discrete Event Dynamical Systems, p. 0, vol. 0, (2012). Submitted,

Books or Other One-time Publications

L. Li, M.D. Lemmon, and X. Wang, "Event-triggered state estimation in vector linear processes", (2010). Conference paper, Published
Bibliography: Proceedings of the American Control Conference, Baltimore, MD, July 2010

P. Wan and M.D. Lemmon, "Optimal power flow in microgrids using event-triggered optimization", (2010). conference paper, Published
Bibliography: Proceedings of the American Control Conference, Baltimore, MD, July 20102

X. Wang and M.D. Lemmon, "Asymptotic stability in distributed event-triggered networked control systems with delays", (2010). conference paper, Published
Bibliography: Proceedings of the American Control Conference, Baltimore, MD, July 2010

M.D. Lemmon, "Event-triggered feedback in control, estimation, and optimization", (2010). book chapter, Published
Editor(s): A. Bemporad, M. Heemels, and M. Johannsson
Collection: Networked Control Systems
Bibliography: editors A. Bemporad, M. Heemels, M. Johansson, Volume 405 Lecture Notes in Control and Information Sciences,pages 293-358, Springer-Verlag Berlin Heidelburg, 2010.

X. Wang and M.D. Lemmon, "Minimum attention controllers for event-triggered feedback systems", (2011). Conference Proceeding, Published
Collection: Proceedings of the IEEE Conference on Decision and Control
Bibliography: Orlanda Florida

L. Li and M.D. Lemmon, "Performance and average sampling period of sub-optimal triggering in event triggered state estimation", (2011). Conference Proceeding, Published
Collection: IEEE Conference on Decision and Control
Bibliography: Orlando Florida

L. Li and M.D. Lemmon, "Weakly coupled event triggered output feedback system in wireless networked control systems", (2011). Conference Proceeding, Published
Collection: Allerton Conference on Communication, Control and Computing
Bibliography: Univ. of Illinois at Urbana Champaign

Lichun Li, Bin Hu, M.D. Lemmon, "Resilient Event Triggered Systems with Limited Communication", (2012). proceedings, Published
Bibliography: IEEE Conference on Decision and Control

Lichun Li, X. Wang, M.D. Lemmon, "Stabilizing bit-rates for perturbed event-triggered control systems", (2012). proceedings, Published
Bibliography: IFAC Conference on Analysis and Design of Hybrid Systems

Lichun Li,M.D. Lemmon, X. Wang, "Stabilizing bit-rates in quantized event triggered control systems", (2012). proceedings, Published

Bibliography: Hybrid Systems: computation and control

Web/Internet Site

URL(s):
http://www.nd.edu/~lemmon/projects/NSF-05-1518/
Description:
This is the project's website.

Other Specific Products

Product Type:
Audio or video products
Product Description:
video of 3DOF helicopter under event-triggered feedback control.
Sharing Information:
Video published over web at URL http://www.nd.edu/~lemmon/projects/NSF-05-1518/heli-movie/

Contributions

Contributions within Discipline:
The findings of this project have contributed to the field of digital control by deriving novel event-triggered output feedback controllers that enforce a system's mean square stability.

The findings of this project have contributed to the field of networked control systems by determining a method for implementing event-triggered transmissions in networked control systems that explicitly account for dropped and delayed transmissions.

The findings of this project have contributed to the field of wireless sensor-actuator networks by demonstrating that distributed event-triggered optimization algorithms can greatly reduce the communication overhead used in implementing distributed optimization algorithms.

Contributions to Other Disciplines:
This project's findings are contributing to power system applications. The PI is helping a small business (Odyssian LLC) to develop wireless networks for economically dispatching power in electrical microgrids. This work is being done in collaboration with power groups at the University of Wisconsin Madison (R. Lasseter) and University of Illinois - Urbana-Champaign (P. Krein). More recent collaborations with GE Energy has examined the use of coupled microgrids in providing reactive support for mid-voltage distribution feeders.

Contributions to Human Resource Development:
1) Training of graduate student Lichun Li, Bin Hu, and Pu Wan

2) Pu Wan (2009), Event-triggered distributed algorithms for network optimization, Ph.D. Dissertation,Department of Electrical Engineering, University of Notre Dame, November 2009
currently employed at Newfield Wireless, Berkeley CA.

3) Development and web dissemination of course materials for graduate course on Cyber-Physical Systems (http://www.nd.edu/~lemmon/courses/cps/)

4) Lichun Li (2011), Event Triggered State Estimation and Output Feedback in Cyber-Physical Systems, Ph.D. Proposal, Dept. of Electrical Engineering, University of Notre Dame, May 2011.

Contributions to Resources for Research and Education:
The project's PI has created a power electronics course (undergraduate level) at the University

of Notre Dame. The unique aspects of this course will be its focus on the control of such circuits particularly with regard to grid-connected systems.

Contributions Beyond Science and Engineering:

Conference Proceedings

Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Contributions: To Any Beyond Science and Engineering

Any Conference