Annual Report for Period: 10/2009 - 09/2010
Submitted on: 07/06/2010
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.

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
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. 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.

The following journal papers were accepted for publication:
1) X. Wang and M.D. Lemmon, Event-triggering in distributed networked control systems, IEEE Transactions on Automatic Control, tentatively scheduled to appear in March 2011.

The following journal paper has 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.

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).

Dr. Lemmon (January 2010) completed a book chapter on event-triggered control for a Springer book on Networked Control Systems to appear in late 2010.

Dr. Lemmon (Spring semester 2010) 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.

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). Another finding over this period was that this approach could also be applied to event-triggered output feedback controllers (Li/Lemmon submitted to CDC 2010). 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).

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).

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.

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.

Journal Publications

X. Wang and M.D. Lemmon, "Event-triggering in distributed networked control systems", IEEE Transactions on Automatic Control, p. , vol. , (2010). Accepted,

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

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, Accepted
Editor(s): A. Bemporad, M. Heemels, and M. Johannsson
Collection: Networked Control Systems
Bibliography: Springer-verlag book to appear in late 2010 or early 2011. 2

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).

Contributions to Human Resource Development:
1) Training of graduate student Lichun Li 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/)

Contributions to Resources for Research and Education:

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 Resources for Research and Education

Contributions: To Any Beyond Science and Engineering

Any Conference