Annual Report for Period: 09/2008 - 08/2009
Submitted on: 06/12/2009
Principal Investigator: Lemmon, Michael D.
Award ID: 0720457
Organization: University of Notre Dame
Submitted By:
Lemmon, Michael - Principal Investigator
Title:
CSR-EHS:Integrating Decentralized Control and Real-Time Scheduling for Networked Dynamical Systems

Project Participants

Senior Personnel

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

Name: Hu, Xiaobo
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Wang, Xiaofeng
Worked for more than 160 Hours: Yes
Contribution to Project:
This person is the lead in developing event-triggered and self-triggered abstractions of dynamical systems.

Name: Chantem, Thidapat
Worked for more than 160 Hours: Yes
Contribution to Project:
This person is developing real-time scheduling methods for event-triggered and self-triggered broadcasts in networked dynamical systems.

Name: Chen, Cong
Worked for more than 160 Hours: Yes
Contribution to Project:
masters level student implementing event-triggered feedback on the real-time shark kernel using a generalized elastic scheduling module

Name: Li, Lichun
Worked for more than 160 Hours: Yes
Contribution to Project:
This graduate student has been developing methods for event-triggered estimation in wireless sensor networks

Name: Wan, Pu
Worked for more than 160 Hours: Yes
Contribution to Project:
This graduate student has been developing event-triggered protocols for distributed optimization in wireless sensor-actuator networks.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

EmNet LLC

EmNet LLC is a small company in South Bend Indiana that was started to help build the CSOnet embedded sensor-actuator network. The results of this NSF project are of direct use to the CSOnet project. We have been working with EmNET LLC to evaluate the relevance of employing event-triggered sampling in the CSOnet system.

Odyssian LLC

Odyssian is a small business in South Bend Indiana that has been working to develop intelligent control architectures for military microgrids. This partner's microgrid application has been used as a basis for demonstrating some of this project's developments with regard to event-triggered distributed optimization. We've used event-triggered optimization as a distributed means of solving the generation dispatch and demand response problems associated with managing electrical power grids.

Other Collaborators or Contacts

As a part of this project, I've made contacts with a number of European investigators (A. Cervin, M. Heemels, and A. Bemporad). In the year 2008, these contacts resulted in an invitation to prepare an invited paper to the 2009 European Control Conference. We were also invited to present our work on CSOnet at the kick-off meeting (Sept 2008) to a EU project that is building an embedded sensor-actuator network for the water distribution network in Barcelona.
In July of 2009, Dr. Lemmon was invited to lecture at a Ph.D. summer school at the University of Siena regarding the event-triggered and self-triggered methodologies being investigated under this NSF grant.
In April of 2009, Dr. Lemmon and his student P. Wan began discussions with Dr. Xue Liu (McGill University) regarding the use of our event-triggered distributed optimization methods in sensor networks.

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, New Orleans, Louisiana, USA, December 2007.
2) IEEE Real-Time Systems Symposium, Tuscon Arizona, USA, December 2007
3) International Workshop on Mobile Device and Urban Sensing (MODUS), St. Louis, MO. April 2008.
4) Hybrid Systems: computation and control, St. Louis, MO. April 2008
5) American Control Conference, Seattle, WA, USA, June 2008

6) 17th International Federation of Automatic Control (IFAC) World Congress, Seoul Korea, July 2008
7) European Conference on Real-Time Systems (ECRTS), Prague, Czech Republic, July 2008.
8) IEEE Conference on Decision and Control, December 2008, Cancun Mexico.
9) Hybrid Systems: computation and control, San Francisco, April 2009.
10) Information Processing in Sensor Networks, San Francisco, April 2009.
11) American Control Conference, St. Louis, MO, June 2009.
12) European Control Conference, Budapest, Hungary, August 2009.

The following journal papers were submitted for publication
1) X. Wang and M. Lemmon, Event-triggering in distributed networked control systems, submitted to IEEE Transactions on Automatic Control, July 2009.
2) P. Wan and M. Lemmon, Event-triggered distributed algorithms for network utility maximization, submitted to IEEE Transactions on Automatic Control, April 2009.

The following journal papers have been published and appeared.
1) X. Wang, and M. Lemmon, Self-triggered Feedback Control Systems with Finite Gain L2 Stability, IEEE Transactions on Automatic Control, volume 45, number 3, pages 452-467, March 2009.
2) T. Chantem, X.S. Hu, and M.D. Lemmon, Generalized Elastic Scheduling for Real-Time Tasks, IEEE Transactions on Computers, volume 58, number 4, pages 480-495, March 2009.

Dr. Lemmon participated in the Cyber-Physical System (CPS) summit in St. Louis MO, April 2008.

Dr. Lemmon participated in the NSF sponsored workshop on cyber-physical electrical systems (CPES) in Baltimore MD, June 2009.

Dr. Lemmon gave an invited presentation to IndianaÆs RF radio alliance entitled ô Notre DameÆs CSOnet Project: How to Group a Start-up from the groundö, Fort Wayne, IN, October 2007.

Dr. Lemmon served as Guest Editor on a special issue of the ACM Transactions on Autonomous and Adaptive Systems (Self-Adaptive and Self-Organizing Wireless Networks).

Dr. Lemmon helped organize an invited session on cyber-physical systems to the 2009 IEEE Conference on Decision and Control (CDC), Shanghai, P.R. China.

Dr. Lemmon and Mr. Wang worked with EmNET LLC to build a hardware testbed of the CSOnet control system. This small scale model of the CSOnet system was used to verify the distributed control system being used in CSOnet.

Dr. Lemmon, Ms. Chantem, and Mr. Chen began work implementing the generalized elastic scheduling service in the real-time Shark kernel (University of Pisa). This platform will be used to study implementations of event-triggered and self-triggered feedback control systems.
In Spring of 2009, Ms. Chantem passed her work onto a new student, Shengyan Hong. By the beginning of summer, Mr. Hong had completed implementing the generalized elastic scheduling service on the shark kernel.
In summer 2009, Mr. Chen finished his work on the real-time Shark kernel. Mr. Chen developed an event-triggered real-time controller for a 3 degree-of-freedom helicopter. During this period, Mr. Chen finished his M.S. degree and his work on the shark kernel has been taken over by Mr. Jorge Viramontes Perez. Mr. Perez will develop implementations of self-triggered controllers for

the helicopter system using the Shark Kernel.

Dr. Lemmon worked with a small company (Odyssian LLC) to implement an event-triggered distributed approach to generation dispatch in military microgrids, (March 2008-February 2009)

Dr. Lemmon wrote and delivered a lecture on event-triggering in control, estimation, and optimization to a Ph.D. summer school at the University of Siena, Italy, in July 2009.

Findings:

This project is based on the conjecture that self-triggered or event-triggered feedback could provide an extremely efficient way of implementing networked control systems over wireless communication networks. A major finding supporting this conjecture was that it is possible to obtain closed form expressions for the maximum admissible time interval (MATI) required for L2 stability in single processor real-time control systems. A remarkable feature of these bounds is that they are state dependent, thereby providing a method for the closed-loop adjustment of task period on the basis of the applicationÆs (control systemÆs) current state. Experimental results from simulation studies indicated that these bounds were very tight for linear time-invariant dynamical systems. Much tighter, in fact, that state-independent bounds for the MATI that are currently found in the open literature. These findings were reported in an IFAC conference publication and a journal version of the paper has appeared in the IEEE Transactions on Automatic Control (March 2009). This original work assumed that the process noise disturbing our system goes to zero as the state approaches its equilibrium point. We relaxed this restriction to any bounded disturbance (reported in American Control Conference 2009).

The techniques used in bounding the MATI for single processor real-time control systems were extended to distributed networked control systems in two papers that were presented at the Hybrid Systems: computation and control workshop as well as at an invited session at the 2008 American Control Conference. The results in these papers show that we can obtain similar state-dependent bounds on the time interval between successive broadcasts. The consequence of this finding is that it provides a firm analytical basis for scheduling access to the communication medium. Future work will examine how we can use these bounds to develop efficient and reliable medium access control protocols in support of networked control applications. Additional findings in this area provided a complete characterization of the impact that delay and data dropouts have on the performance of the networked control system. These findings were reported at the hybrid systems computation and control workshop (HSCC) in April 2009. A journal paper based on these results was submitted to the IEEE Transactions on Automatic Control in July of 2009.

An additional finding, whose development was partially supported by this grant, was that we can extend the elastic scheduling framework developed by G. Buttazzo to a much larger set of task models. In particular, we were able to show that ButtazzoÆs elastic scheduling algorithm actually solves a specific optimization problem. With this observation, we were able to show that the elastic scheduling paradigm could be applied to a variety of other task models and other optimization objectives. In particular, a recent paper (accepted for publication in the IEEE Transactions on Computers) developed an elastic scheduling algorithm for periodic task models in which the deadline was less than the period. One possible application of these results would be to schedule event-triggered control tasks using the MATI bounds developed by this project. We are currently working to implement this system in the real-time Shark kernel developed by the University of Pisa.

An important finding was made regarding the use of event-triggered methodologies in solving distributed optimization problems. In particular, we've developed a distributed event-triggered algorithm for solving network utility maximization (NUM) problems often found in network congestion control applications. These methods also have application to other domains in particular generation dispatch and demand response shaping in electrical power grids. The major finding of this work is that event-triggering can reduce the message passing complexity of distributed NUM algorithms (such as dual-decomposition) by two orders of magnitude. Additional experimental results suggest that the message passing complexity of the event-triggered algorithm is nearly scale free. The earliest version of this work was reported at the European control conference (ECC) in August 2009. Substantially improved methods were developed based on primal and primal-dual implementations of an augmented Lagrangian approach to the NUM problem. These later results were reported at the American Control Conference (ACC 2009) and the Information Processing in Sensor Networks (IPSN 2009) workshop.

At the beginning of summer 2009, our group began looking closely at the use of event-triggering in distributed estimation and data fusion applications. We consider a finite horizon version of the problem, in which sensors decide when to send samples in an event-triggered manner over a finite horizon of time. Sampling decisions must be made in a way that minimize the estimation error at the data fusion center subject to a fixed constraint on the sensors' broadcast rate. Dynamic programming was used to obtain a practical method for computing the event-threshold functions. It appears possible to use this finite-horizon approach to event-triggered estimation as the basis for a receding-horizon type of approach to estimation and data fusion in sensor networks.

Training and Development:

Through our interaction with EmNET LLC, we've been able to provide the graduate students working on this NSF project with a practical real-life platform upon which to base their theoretical research.

One of the students (Xiaofeng Wang) taught a graduate level 'optimal control' course in the Fall 2008 semester at Notre Dame

One of our students (Mr. Cong Chen) completed his M.S. degree in August 2009.

One of our students (Mr. Xiaofeng Wang) completed the defense of his Ph.D. dissertation in July 2009 and will begin working as a post-doctoral researcher at the University of Illinois, Urbana-Champaign.

Outreach Activities:

Have participated in the Indiana RF Alliance (a small consortium of Indiana-based industries and agencies) to educate that group about the use of distributed feedback control in the CSOnet project.

Presentation and follow on discussion concerning CSOnet project at LaSalle middle school's after school program (December 2008).

Journal Publications

Chantem T.; Hu X.; Lemmon M., "Generalized Elastic Scheduling for Real-time Tasks", IEEE Transactions on Computers, p. , vol. 58, (2009). Published, 10.1109/TC.2008.175

Wang X.; Lemmon M., "Self-triggered Feedback Control Systems with Finite-Gain L2 Stability", IEEE Transactions on Automatic Control, p. 45, vol. 54, (2009). Published, 10.1109/TAC.2009.2012973

X. Wang and M.D. Lemmon, "Event-triggering in distributed networked control systems", IEEE Transactions on Automatic Control, p. , vol. , (2009). Submitted,

P. Wan and M.D. Lemmon, "Event-triggered distributed algorithms for Network Uitlity Maximization", IEEE Transactions on Automatic Control, p. , vol. , (2009). Submitted,

Books or Other One-time Publications

T. Chantem, X.S. Hu, and M.D. Lemmon, "Period and Deadline Selection Problem for Real-Time Systems", (2008). conference proceeding, Published
Bibliography: Real-Time Systems, 2008. ECRTS '08. Euromicro Conference on, 2-4 July 2008, page 168 - 177, Prague, DOI-10.1109/ECRTS.2008.35

L. Montestruque and M.D. Lemmon, "CSOnet: a metropolitan scale wireless sensor-actuator network", (2008). conference proceeding, Published
Collection: International Workshop on Mobile Device and Urban Sensing (MODUS)
Bibliography: appears in Proceedigns for International Workshop on Mobile Device and Urban Sensing (MODUS), St. Louis, MO, April 2008.

P. Wan and M. Lemmon, "Event triggered distributed optimization in sensor networks", (2009). conference proceeding, Published
Collection: Information Processing in Sensor Networks (IPSN)
Bibliography: Information Processing in Sensor Networks (IPSN), pages 49-60, San Francisco, CA, April 13-16, 2009.

P. Wan and M. Lemmon, "Distributed Network Utility Maximization using Event-triggered augmented Lagrangian methods", (2009). conference proceeding, Published
Bibliography: Proceedings of the American Control Conference, June 10-12, 2009, St. Louis, MO.

X. Wang and M. Lemmon, "Self-triggered Feedback Systems with State-Independent Disturbances", (2009). conference proceeding, Published
Bibliography: Proceedings of the American Control Conference, June 10-12, 2009, St. Louis, MO.

P. Wan and M. Lemmon, "Distributed Network Utility Maximization using Event-Triggered Barrier Methods", (2009). conference proceeding, Published
Bibliography: Proceedings of the European Control Conference, August 23-26, 2009, Budapest, Hungary

X. Wang and M. Lemmon, "Finite Gain L2 Stability in Distributed Event-Triggered Networked Control Systems with Data Dropouts", (2009). conference proceeding, Published
Bibliography: Proceedings of the European Control Conference, August 23-26, 2009, Budapest, Hungary

X. Wang and M. Lemmon, "Event Design in Event-Triggered Feedback Control Systems", (2008). conference proceeding, Published
Bibliography: Proceedings of the IEEE Conference on Decision and Control, December 9-11, 2008, pages 2105-211, Cancun Mexico, DOI 10.1109/CDC.2008.4739105

X. Wang and M. Lemmon, "State based Self-triggered feedback control systems with L2 stability", (2008). conference proceeding, Published
Bibliography: Proceedings of the 17th IFAC world congress, Seoul Korea, July 5-11, 2008.

Web/Internet Site

URL(s):
http://www.nd.edu/~lemmon/projects.html

Description:
This site briefly describes and links to papers generated by Dr. Lemmon's active projects.
This NSF project is included on that site.

Other Specific Products

Contributions

Contributions within Discipline:
The findings of this project have contributed to the field of digital-control by deriving state-dependent estimates of sampling periods required for L2 system stability.

The findings of this project have contributed to the field of networked control systems by determining bounds on acceptable periods, dropouts, and delays under which the networked system's performance is guaranteed.

The findings of this project have contributed to the field of wireless sensor networks by showing that the use of event-triggering can greatly reduce the message passing complexity of distributed optimization algorithms.

The findings of this project have contributed to the field of real-time scheduling theory by developing an elastic scheduling algorithm for periodic tasks where deadline is less than period.

Contributions to Other Disciplines:
The distributed control techniques being developed in this project are being applied to civil-engineering applications controlling water distribution and wastewater flows. The distributed control techniques are also being used to develop controllers for electrical microgrids.

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:
A set of lectures on event-triggered and self-triggered feedback for use in control, estimation, and optimization was prepared for a Ph.D. summer school in Siena Italy (July 2009). These lectures will be made available on the web and will serve as the basis for a contribution to a book on networked control systems being assembled by the summer school's organizers.

Contributions Beyond Science and Engineering:

Conference Proceedings

Chantem, T;Wang, XF;Lemmon, MD;Hu, XS, Period and deadline selection for schedulability in real-time systems, "JUL 02-04, 2008", ECRTS 2008: PROCEEDINGS OF THE 20TH EUROMICRO CONFERENCE ON REAL-TIME SYSTEMS, : 168-177 2008

Wang, XF;Lemmon, MD, Event-Triggering in Distributed Networked Systems with Data Dropouts and Delays, "APR 13-15, 2009", HYBRID SYSTEMS: COMPUTATION AND CONTROL, 5469: 366-380 2009

Wang, XF;Lemmon, MD, Event-triggered broadcasting across distributed networked control systems, "JUN 11-13, 2008", 2008 AMERICAN CONTROL CONFERENCE, VOLS 1-12, : 3139-3144 2008

Wang, XF;Lemmon, MD, Decentralized event-triggered broadcasts over networked control systems, "APR 22-24, 2008", HYBRID SYSTEMS: COMPUTATION AND CONTROL, 4981: 674-677 2008

Special Requirements

Special reporting requirements: None
Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Product
Contributions: To Any Human Resource Development
Contributions: To Any Beyond Science and Engineering