Annual Report for Period: 09/2009 - 08/2010   **Submitted on:** 07/06/2010

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:

      Project PI leading effort on self-triggered control

      Name: Hu, Xiaobo

      Worked for more than 160 Hours: Yes

      Contribution to Project:

      Project co-pi leading effort on real-time scheduling

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.

      Name: Viramontez-Perez, Jorge

Worked for more than 160 Hours: Yes
Contribution to Project:
Developed event-triggered implementation of 3DOF helicopter system

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

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Organizational Partners
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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.

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Other Collaborators or Contacts
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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.
In 2010, the project contacted R. Lasseter (Univ of Wisconsin Madison) through a joint project with Odyssian LLC to obtain details of UWM's microgrid testbed. The resulting information was used to develop event-triggered power dispatch algorithms for microgrids.

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Activities and Findings
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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.

13) Real-time Systems Symposium, Washington DC, December 2009

14) IEEE Conference on Decision and Control, Shanghai, China, December 2009

15) American Control Conference, Baltimore, MD, July 2010

16) Euromicro conference on real-time systems (ECRTS10), Brussels, Belgium, July 2010.

The following journal papers were submitted for publication

1) 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 accepted for publication.

1) J. Yi, C. Poellabauer, X.S. Hu, and L. Zhang, Minimum Bandwidth Reservations for Periodic Streams in Wirleess real-time Systems, accepted for publication in IEEE Transactions on Mobile Computing, 2010.

2) Y. Yu, S. Ren, and X.S. Hu, A metric for judicious relaxation of timing constraints in soft real-time systems, accepted for publication in ACM transactions on design automation of electronic systems, 2010.

3) X. Wang and M. Lemmon, Event-triggering in distributed
networked control systems, accepted for publication in IEEE Transactions on Automatic Control, 2010

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.

3) X. Wang and M.D. Lemmon, Self-triggering under state-independent disturbances, IEEE Transactions on Automatic Control, volume 55, issue 6, pages 1494-1500, June 2010.

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 Indiana's RF radio alliance entitled 'Notre Dame's CSOnet Project: How to Group a Start-up from the ground', 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 delivered two invited lectures (December 2009) at the University of Science and Technology China (USTC) in Hefei 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 developed

implementations of event-triggered controllers for the helicopter system using the Shark Kernel. This work was completed in spring (May) of 2010.

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). This work is continuing with phase 2 STTR contract for 2010-2011.

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.

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. Hu will serve as chair for the hardware/software integration and co-design track at the real-time and embedded technology and applications symposium (RTAS 2011).

Xiaofeng Wang successfully defended his Ph.D. dissertation (Event-triggering in cyber-physical systems) in June of 2009.

Pu Wan successfully defended his Ph.D. dissertation (Event-triggered distributed algorithms for network optimization), in November 2009.

Jorge Viramontes Perez successfully completed his M.D. degree in electrical engineering in May of 2010.

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 application's (control system's) current state. Experimental results from simulation studies indicated that these bounds were very tight for linear time-invariant dynamical systems. Much tighter, in fact, than 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). That work was also published in the IEEE Transactions of automatic control in June 2010.

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 accepted for publication in the IEEE Transactions on Automatic Control and is tentatively scheduled to appear in March 2011.

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 Buttazzo's 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 (published in the IEEE Transactions on Computers in 2009) 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. This integration was completed in May 2010 with an implementation of event-triggered control of a 3DOF helicopter. A movie of this system will be found on the project's website.

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 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. These distributed optimization concepts were applied to the power dispatch problem in microgrids (ACC 2010) as part of the on-going collaboration with Odyssian LLC.

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. Initial work with regard to distributed estimation with transmission constraints appeared in the 2010 American Control Conference. A key part of this work was to reduce the computational complexity of the scheme by employing a suboptimal family of quadratic forms to characterize the decision logic. This idea was later extended to output feedback control with transmission constraints in a paper that was submitted to the 2010 Conference on Decision and Control.

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

Mr. Cong Chen completed his M.S. degree in August 2009.

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.

Mr. Pu Wan completed the defense of his Ph.D. dissertation in November 2009 and will begin working as a research engineer at Newfield Wireless in Berkeley California.

Mr. Jorge Viramontes-Perez completed his M.S. degree in electrical engineering in May 2010 and is working as a controls engineer with GE aviation in Mexico.

Outreach Activities:

The PI 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.

The PI gave a presentation and follow on discussion concerning CSOnet project at LaSalle middle school's after school program (December 2008).

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Journal Publications

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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. , (2010). Accepted,

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

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

Y. Yu, S. Ren, and X.S. Hu, "A metric for judicious relaxation of timing constraints in soft real-time systems", ACM transactions on design automation of electronic systems, p. , vol. , (2010). Accepted,

Books or Other One-time Publications

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, "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.

X. Wang, "Event-triggering in Cyber-physical Systems", (2009). Thesis, Published
Bibliography: PH.D. Dissertation, Department of Electrical Engineering, University of Notre Dame, June 2009

Pu Wan, "Event-triggered distributed algorithms for network optimization", (2009). Thesis, Published
Bibliography: Ph.D. dissertation, Dept. of Electrical Engineering, University of Notre Dame, November 2009

P. Wan and M.D. Lemmon, "An event-triggered distributed primal-dual algorithm for network utility maximization", (2009). conference paper, Published
Bibliography: Proceedings of the IEEE Conference on Decision and Control (CDC), Shanghai, China, December 20092

Web/Internet Site

URL(s):
http://www.nd.edu/~lemmon/projects/NSF-07-504/

Description:

This is the project's website.

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:

Project provided opportunity for graduate student (X. Wang) to teach course in optimal control.

Project graduated 2 Ph.D. students (X. Wang and P. Wan) and 2 MS students (C. Chen and J. Viramontez Perez).

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.

These lectures were turned into a chapter in a book on Networked Control Systems that should appear in late 2010.

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

Wan, P;Lemmon, MD, Event-triggered Distributed Optimization in Sensor Networks, "APR 13-16, 2009", 2009 INTERNATIONAL CONFERENCE ON INFORMATION PROCESSING IN SENSOR NETWORKS (IPSN 2009), : 49-60 2009

Wan, P;Lemmon, MD, Distributed Network Utility Maximization using Event-triggered augmented Lagrangian methods, "JUN 10-12, 2009", 2009 AMERICAN CONTROL CONFERENCE, VOLS 1-9, : 3298-3303 2009

Wang, XF;Lemmon, MD, Self-Triggered Feedback Systems with State-Independent Disturbances, "JUN 10-12, 2009", 2009 AMERICAN CONTROL CONFERENCE, VOLS 1-9, : 3842-3847 2009

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 Beyond Science and Engineering