Annual Report for Period:09/2010 - 08/2011
Submitted on: 06/28/2011
Principal Investigator: Lemmon, Michael D.
Award ID: 0931195
Organization: University of Notre Dame
Submitted By:
Lemmon, Michael - Principal Investigator
Title:
CPS: Small: Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

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: Hong, Shengyan
Worked for more than 160 Hours: Yes
Contribution to Project:
Development of elastic scheduling algorithms in wireless networks

Name: Liu, Jie
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr. Liu is studying the use of network coding in wireless networked control systems.

Name: Xia, Meng
Worked for more than 160 Hours: Yes
Contribution to Project:
Ms. Xia is studying distributed optimization of wireless networked control systems

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 customer's 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

The project has made contact with Dr. Qiang Ling (University of Science and Technology China - Hefei P.R.C.). Dr. Ling is an expert in quantized feedback control and has worked with Dr. Lemmon to examine some aspects of quantized control under dropouts.

Activities and Findings

Research and Education Activities:

Activities Report - 0931195 - Sept 2009 - July 2011

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

1) [CDC09] IEEE Conference on Decision and Control, Shanghai, China, December 2009

2) [RTSS09] IEEE Real-time Systems Symposium, Washington DC, USA December 2009

3) [ECC09] European Control Conference, Budapest, Hungary, August 2009

4) [ACC10] American Control Conference, Baltimore, MD, July 2010

5) [ECRTS10] Euromicro Conference on Real-time Systems (ECRTS), Brussels, Belgium, July 2010.

6) [CDC10] Conference on Decision and Control, Atlanta, GA, December 2010

7) [HSCC11] Hybrid Systems Computation and Control, Chicago, IL, April 2011

8) [RTAS11] IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), Chicago, IL, April 201

The following conference papers were presented

1) [Hong09] Shengyan Hong, X.S. Hu and M.D. Lemmon, An adaptive approach to reduce control delay variations, Real-time Systems Symposium, work-in-progress session, Washington D.C., December 2009.

2) [Hong10] S. Hong, X.S. Hu, and M.D. Lemmon, Reducing delay jitter of real-time control tasks through adaptive deadline adjustments, Euromicro Conference on Real-time Systems (ECRTS10), Brussels, Belgium, July 2010

3) [Ling10] Q. Ling and M.D. Lemon, Input-to-state stabilizability of quantized linear control systems under feedback dropouts, Proceedings of the American Control Conference, Baltimore, MD, June 29 - July 2, 2010.

4) [Lemmon11] M.D. Lemmon and X.S. Hu, Almost sure stability of networked control systems under exponentially bounded bursts of dropouts, Hybrid Systems: computation and control (HSCC 2011), Chicago, USA, April 2011.

5) [Hong11] S. Hong, X.S. Hu, and M.D. Lemmon, An adaptive transmission rate control approach to minimize energy consumption, Work-in

Progress Session, IEEE Real-time and Embedded Technology and Applications Symposium, Chicago IL, USA April 2011.

6) [Hong11a] S. Hong, T. Chantem, and X. Hu, Meeting end-to-end deadlines through distributed local deadline assignment, IEEE Real-time and Embedded Technology and Applications Symposium (RTAS) - Work-in-Progress Session, April 2011.

The following course materials were developed

1) [Lemmon10] M.D. Lemmon, Formal Methods in the Design and Verification of Cyber-Physical Systems, Spring semester 2010, Dept. of Electrical Engineering and Dept. of Computer Engineering, University of Notre Dame, http://www.nd.edu/~lemmon/courses/cps/

2) [Lemmon11] M.D. Lemmon, Special Studies in Networked Control Systems, Spring semester 2011, Dept. of Electrical Engineering, University of Notre Dame, http://www.nd.edu/~lemmon/courses/special-studies

The following journal papers were published

1) [Yi11] J. Yi, C. Poellabauer, X.S. Hu, and L. Zhang, Minimum bandwidth reservations for periodic streams in wireless real-time systems, IEEE Transactions on Mobile Computing, volume 10, issue 4, pages 479-490, 2011.

2) [Ling10a] Q. Ling and M.D. Lemmon, A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise, IEEE Transactions on Automatic Control, volume 55, number 11, pages 2590-2596, Nov. 2010.

3) [Ling10b] Q. Ling, M.D. Lemmon and H. Lin, Asymptotic stabilization of dynamically quantized nonlinear systems in feedforward form, Journal of Control theory and Applications, volume 8, number 1, pages 27-33, February 2010.

The following paper was submitted for conference publication

1) [Xia11] M. Xia and M.D. Lemmon , Event-triggered network utility maximization through consensus filtering, submitted to IEEE Conference on Decision and Control, December 2011.

The following Ph.D. dissertations were completed under this project

1) [Wan09] Event-triggered distributed algorithms for network optimization, Ph.D. dissertation, Dept. of Electrical Engineering, University of Notre Dame, November 2009.

2) [Chantem11] Real-time system design under Physical and Resource Constraints, Ph.D. Dissertation, Dept. of Computer Science and Engineering, University of Notre Dame, April 2011.

The following invited talk was given

1) [Lemmon11a] Performance of Networked Control Systems under Sporadic Feedback, presentation at KTH, Stockholm Sweden, March 21, 2011.

Findings:

A major theme in this project concerns the ability of control applications to dynamically adjust the real-time resources they require. Resource utilization is usually a function of task parameters such as period and deadline. Nontraditional approaches, however, can be employed in which the controller adjusts the task size by changing feedback quantization levels or in which the controller breaks apart the feedback task into a number of dependent subtasks. Findings for 2009 examined these nontraditional approaches to real-time task management.

The first major findings [Hong09,Hong10] examined feedback controllers in which the control task was divided into a set of dependent subtasks. For control applications this involves
partitioning the control task into at least three subtasks, an initial subtask that measures the system state, one or more subtasks
that compute the control, and a final subtask that generates the actual control output. It was shown that this task model allowed a significant reduction in control task jitter. In building wireless networks for real-time applications, it therefore makes sense to again partition the feedback stream into a group of dependent subtasks. This should provide greater flexibility in scheduling transmissions over the network so it becomes

easier to meet real-time scheduling constraints.

A second major finding concerned the relationship between the stability of quantized control systems and the sequence of dropped feedback packets [Ling10, Ling10a, Ling10b]. These results showed that a meaningful real-time QoS constraint for feedback controllers should be based on a windowed characterization of the dropout rate (rather than an average dropout rate). Since this is consistent with traditional firm real-time task models, it suggests that our wireless network QoS requirements should also focus on maintaining firm real-time guarantees on packet delivery.

Another major component of this project involves controlling the wireless network to maximize the real-time capacity of the network. Initial modeling efforts assumed that packet routing was fixed. NS2 simulations made it apparent, however, that interference between competing routes plays a major role in limiting the real-time performance of these networks. It was therefore realized that the project would need to adopt a more realistic physical model for interference. Since real-time performance relies on ensuring some degree of determinism within the network, it was decided that the project should actively control interference using distributed price-based power control algorithms. By controlling interference, one essentially provides a 'stable' environment in which it becomes possible to support firm real-time traffic. The project is currently studying how to build such power control algorithms for firm real-time systems with the long-term goal of formalizing the notion of a network's real-time capacity.

We proposed [Hong11] an online transmission rate selection approach based on an offline optimal dynamic voltage frequency scaling algorithm. Our approach exploits the periodicity property of the real-time streams to predict the future jobs' timing information and find an optimal transmission rate schedule. We are extending our approach to make more messages meet their deadlines. Preliminary results show that our approach achieves a higher success ratio with a lower timing cost compared with existing works, although the energy dissipation caused by our approach sees a small increase.

We are studying [Hong11a] the distributed local deadline assignment problem which appears in both multiprocessor systems and multihop networks. We have proposed an approach for solving the problem based on the necessary and sufficient condition introduced in prior work. Our approach exploits the execution information on adjacent processors to find a feasible local deadline assignment. Our optimization approach, however, can be too time consuming for online use. We are in the process of designing an efficient heuristic. Preliminary results indicate that our approach performs much better than existing work.

We examined [Lemmon11] the relationship between control system performance and wireless channel state using a more sophisticated and accurate modeling communication/control framework than has been used in the prior literature. Communication models for packet dropping in wireless channels model exponentially bounded bursts of dropouts. The advantage of this communication model is that it can be used to model fading and it allows us to use the stochastic network calculus to bound a stream's end-to-end quality-of-service (QoS). The impact that this QoS has on control system performance has often been studied using second-order moment stability. In [Lemmon11], we examined the almost sure stability under bursty dropouts. Almost-sure stability is a much stronger stability concept than mean square stability. The paper provides sufficient conditions relating the almost-sure stability of the system to the burstiness of the channel, thereby suggesting new methods for adapting a control system to changes in channel state that would improve the performance of wireless networked control systems.

Recent work (May-July 2011) has built upon the initial work in [Lemmon11] to study the role that dynamic quantization of the feedback information may play in adapting control systems to changes in the wireless channel state. We have recently identified sufficient quantization levels required to assure the noise-to-state stability of discrete-time linear systems under feedback channels with exponential burstiness. These quantization levels are a function of the current channel state and can be used as a constraint guiding the scheduling of packet transmissions in a wireless network control system so that a minimum level of system performance is achieved.

We have proposed [Xia11] the integration of consensus filter estimation into distributed optimization algorithm developed in [Wan09]. The proposed distributed optimization algorithms seek to solve network utility maximization problems whose solution can be used to reconfigure wireless networks. One issue in these algorithms is that they assume link utilization can be directly measured by all agents. In some networked systems this is not possible and the link utilization must be estimated from measurements made at the entry and exit of the link. The algorithms proposed in [Xia11] use a consensus filter to estimate link utilization in a way that is consistent across multiple users. Convergence proofs were obtained and supported through simulation studies.

Training and Development:
This project has trained graduate students (S. Hong, Jie Liu, and Meng Xia) in research skills unifying the development of real-time systems in wireless communication networks.

Outreach Activities:
The project's outreach activities have revolved about interactions with Notre Dame's department of biological sciences. The PI has helped guide the introduction of sensor network technology into projects attempting to control nutrient loading in streams and lakes due to agricultural runoff (http://www.nd.edu/~lemmon/projects/ND-ECI/). This project is a collaboration between biological sciences (J. Tank - Notre Dame), department of economics (M. Lipscomb - ND), dept. of electrical engineering (M.D. Lemmon - ND), and the nature conservancy.

Journal Publications

Q. Ling and M.D. Lemmon, "A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise", IEEE Transactions on Automatic Control, p. 2, vol. 55, (2010). Published, 10.1109/TAC.2010.2063150

J. Yi , C. Poellabauer, X.S. Hu, and L. Zhang, "Minimum bandwidth reservations for periodic streams in wireless real-time systems", IEEE Transactions on Mobile Computing, p. 479, vol. 4, (2010). Published, 10.1109/TMC.2010.190

Q. Ling, M.D. Lemmon, and H. Lin, "Asymptotic stabilization of dynamically quantized nonlinear systems in feedforward form", Journal of Control Theory and Applications, p. 27, vol. 8, (2010). Published, 10.1007/s11768-010-9186-8

Books or Other One-time Publications

Shengyan Hong, X. S. Hu, and M.D. Lemmon, "An adaptive approach to reduce control delay variations", (2009). conference paper, Published
Bibliography: Proceedings of the Real-time Systems Symposium - work-in-progress session, Washington DC, December 2009

S. Hong, X.S. Hu, and M.D. Lemmon, "Reducing Delay Jitter of Real-time Control Tasks through Adaptive Deadline Adjustments", (2010). Book, Published
Collection: Euromicro conference on real-time systems (ECRTS10), Brussels, Belgium, July 2010
Bibliography: Euromicro conference on real-time systems (ECRTS10), Brussels, Belgium, July 2010

Q. Ling and M.D. Lemmon, "Input-to-state stabilizability of quantized linear control systems under feedback dropouts", (2010). conference paper, Published
Bibliography: Proceedings of the American Control Conference, Baltimore, 2010

M.D. Lemmon and X.S. Hu, "Almost sure stability of networked control systems under exponentially bounded bursts of dropouts", (2011). Conference Proceeding, Published
Collection: Hybrid Systems: computation and control
Bibliography: Chicago, IL, USA

S. Hong, X.S. Hu and M.D. Lemmon, "An adaptive transmission rate control approach to minimize energy consumption", (2011). Conference Proceeding, Published
Collection: IEEE Real-time and Embedded Technology and Applications Symposium
Bibliography: Chiago, IL, USA

S. Hong, T. Chantem, and X. Hu, "Meeting end-to-end deadlines through distributed local deadline assignment", (2011). Conference Proceeding, Published
Collection: IEEE Real-time and Embedded Technology and Applications Symposium, work-in-progress session
Bibliography: Chicago IL, USA

M. Xia and M.D. Lemmon, "Event-triggered Network Utility Maximization through Consensus Filtering", (2011). Conference Proceeding, Submitted
Collection: IEEE Conference on Decision and Control
Bibliography: Orland FL, USA

Web/Internet Site

URL(s):
http://www.nd.edu/~lemmon/projects/NSF-08-611/
Description:
This is the project's website.

Other Specific Products

Contributions

Contributions within Discipline:
The findings of this project are relevant to three different communities; control systems, wireless networking, and real-time systems. The contribution of this project's findings to these areas is itemized below

1. Deadline jitter is reduced by breaking apart a control task into smaller dependent subtasks (real-time systems) [Hong09,Hong10]

2. Firm real-time QoS constraints provide a realistic method for ensuring closed-loop control system performance (control systems and real-time systems) [Ling10,Ling10a].

3. Reservation-based access provide a more effective means of achieving real-time guarantees than contention based access in wireless networks (real-time systems and wireless networking) [Yi10].

4. Exponentially bursty models of dropouts allow us to use the network calculus to assess the impact end-to-end QoS has on a wireless networked control system's performance and stability [Lemmon11].

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).

This project's work with verification of hybrid automata is being applied to the study of regime shifts in ecological systems. The PI is working with Notre Dame's biology department (J. Tank) to use model checking methods to study regime shifts in comparmentalized models of stream ecosystems.

Contributions to Human Resource Development:
Contributions to Human Resource Development are listed below:

1) Training of graduate student S. Hong, Jie Liu, and Meng Xia

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

3) Supporting dissertation work by serving on Ph.D. program committees (T. Chantem and P. Wan)

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:

Any Product
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering
Any Conference