Preview of Award 0931195 - Annual Project Report

Cover

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Project Title:	CPS: Small: Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network
PD/PI Name:	Michael D Lemmon, Principal Investigator Xiaobo S Hu, Co-Principal Investigator
Submitting Official (if other than PD\PI):	N/A
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Recipient Organization:	University of Notre Dame
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Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

*** What are the major goals of the project?**

Wireless sensor-actuator networks (WSAN) consist of numerous sensing and actuation devices that share information over an ad hoc wireless communication network. Examples of such systems include the national power grid, ground/air traffic networks, and water/gas distribution networks.

This project studies the implementation of feedback control algorithms over WSANs, particularly with regard to the management of large-scale networked systems such as the electric power grid or water distribution networks. Controlling such physical processes traditionally requires some type of hard real-time support. This means that each packet of feedback data must be serviced within a specified deadline to assure the overall control application's performance level. It has, in practice, been difficult to provide such guarantees in real-life wireless networks. This project will address that issue by developing algorithms that allow control applications and network servers to work together in maximizing application performance subject to firm or hard real-time service constraints.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: Over its lifetime, this project has supported three major activities

1) The first activity develops algorithms for scheduling transmissions in wireless communication networks that meet either a hard or firm end-to-end deadline. The

message streams are generated by tasks supporting a control system. In general, these streams have either hard or firm real-time deadline constraints and in the case of event-triggered systems, these streams are sporadic, rather than periodic.

2) The second major activity a) identifies probabilistic quality-of-service constraints that assure some appropriate stochastic notion of control system stability and performance and b) determines switching control rules that can provide guarantees on control performance when the network's available QoS changes.

3) The last major activity investigates various real-life wireless sensor-actuator network applications that could benefit from the ideas being studied in this project.

Specific Objectives: The project's main objective is to demonstrate that wireless communication networks can be used in highly critical networked control system applications. Specific project objectives are:

1) Development of algorithms for a multi-hop wireless HART network that can support data streams generated by event-triggered networked control systems.

2) Identify useful stochastic measures of network QoS that assure the almost sure stability of a networked control system.

3) Develop switching control strategies that successfully adapt to abrupt changes in communication channel availability.

4) Evaluate the achievable performance of these control strategies on specific applications.

Significant Results: 1) The project has investigated the problem of balancing packet utility with energy consumption and packet deadline in wireless real-time systems that execute computationally-intensive applications and must transmit packets over the network in a timely manner. We devised an online holistic scheduling framework which explicitly considers packet utility for selecting packets to transmit and guarantee their deadline requirements using both packet and energy-aware job assignment and scheduling. Our framework is applicable to wireless real-time systems equipped with either a single or multi-core processor. Extensive simulation based on realistic processor parameters was conducted. The results show that our proposed method allows for timely transmissions of the most important packets, which helps to control overall system utility, while saving processor energy.

2) We have studied the distributed local deadline assignment problem which appears in both multiprocessor systems and multihop networks. We introduced a distributed approach which combines local-deadline assignment with feasibility analysis such that the resulting deadline assignment is guaranteed to be schedulable. This approach formulates the local-deadline assignment problem as a mathematical programming problem of maximizing the minimum time slack among all the jobs executed on each processor. We further introduce an on-line, iterative technique to efficiently and effectively solve the mathematical programming based local-deadline assignment problem. The proposed algorithm has a polynomial time complexity and is quite fast in practice. Given its distributed nature, the algorithm can readily adapt to dynamic changes in job execution times and execution paths. We have conducted simulation-

based studies of applying our
algorithm to both randomly generated tasks as well as tasks from real-world applications, and made comparisons to
existing representative methods. The results show that our approach indeed leads to improved quality of service for distributed real-time systems.

3) To facilitate systematic exploitation of the interplay between control strategies and implementation alternatives,
we have proposed a new task model that aims to connect directly the control system behavior with real-time task modeling. In this model, the separation interval (i.e., task period) and the maximum allowed delay (i.e., task deadline) are defined as functions of time and external disturbances to the physical system. In addition, the model may allow the system to trade off task execution times with task periods and deadlines. In this way, the dynamics of the control system can be reflected in the task model and be exploited to improve resource utilization. We are developing new online resource management schemes based on the new task model, The new scheme aims to achieve required performance of control applications with minimal resource (e.g., energy) usage.

4) The project has developed event-triggered optimal dispatch algorithms for electrical microgrids. The microgrid is an example of a networked control system that uses local decentralized controls to maintain stability. Determination of local setpoints for each controller can be solved used a distributed optimziation algorithm, in which each generator optimizes its generation cost subject to local physical constraints. Because the system is distributed, it is implemented over a wireless communication network and in order to reduce the information exchange, the project used an event-triggered communication strategy. The results showed that event-triggered optimization was able to achieve the desired performance goal with a great reduction in communication traffic while still assuring voltage stability.

5) The project has developed a method for assuring the resilience of event-triggered control systems realized over a wireless communication network. The problem involves having a system which is "disturbed" away from its operating point to such a degree that it invalidates the codebook that the transmitter and receiver use to encode and decode wireless transmissions. We establish a procedure that recovers the codebook in finite time. This is, to our knowledge, the first work to explicitly consider such failures in such event-triggered systems.

6) The project developed a new stochastic QoS measure that can be directly related to the almost sure stability of a networked control system. This work characterizes the wireless channel as an exponentially bounded bursty (EBB) channel, that bounds the probability of a channel outage as an exponential function of time. The use of such exponential bounds fit well with stochastic network calculus concepts; thereby facilitating the analysis of the entire network's end-to-end quality of service. This measure is also closely related to notions of almost sure stability, thereby providing sufficient conditions under which one can assure the almost sure stability of the networked control system. Almost sure stability is a much stronger stability concept than the usual notion of mean square stability and as a result, systems that possess almost sure stability are well suited to safety-critical applications.

7) The project has applied this new stochastic QoS measure to the development of

resilient leader-follower controls for multi-robot systems. In this case, we use an EBB channel model and identify switching conditions on both controls and sampling times that guarantee almost sure stability of the leader-follower system when the wireless channel experiences deep fades. Simulation results demonstrate the effectiveness of the approach.

Key outcomes or Other achievements:

1) A key outcome of this project is that one does not need wireless communication traffic that is highly deterministic and periodic in nature to assure the performance of a networked control system. The results generated by this project have demonstrated that almost sure performance guarantees can be achieved with sporadic feedback streams whose burstiness is bounded in a precise manner. This is achieved by adopting a control strategy that "switches" between various controllers in response to changes in channel state. In particular, this means that when the channel state deteriorates, the physical plant reduces its performance requirements by switching to a more sluggish control that guarantees stability and safety.

2) The preceding outcome focused on actions that the control might take to adapt to variations in the wireless channel's state. This project originally speculated that one might also try to control the communication network (i.e. the network fabric) to meet the QoS requirements for a given controller. This project has investigated that question by applying real-time scheduling strategies to wireless networking. Results indicate that it is indeed possible to develop sophisticated scheduling schemes that support event-triggered transmission and manage message latency.

3) Scheduling methods can manage end-to-end message latency but this is achieved with the underlying assumption of a time-slotted network architecture whose channels are relatively reliable. When channel states vary in a bursty manner, these algorithms appear to be less successful and this suggests that one may need to take more direct control of the physical channel to meet the stochastic QoS requirements of a given control system. So one additional outcome of this project is the recommendation to begin using direct control of the communication channel in conjunction with distributed scheduling concepts to manage the system's communication fabric.

*** What opportunities for training and professional development has the project provided?**

This project has trained graduate students (S. Hong, Jie Liu, Meng Xia, T. Chantem, Lichun Li, Zhao Wang, Bin Hu and Mingming Cai) in research skills unifying the development of real-time systems in wireless communication networks.

Students (S. Hong and Z. Wang) supported by this project took part in a summer internship program with IBM.

*** How have the results been disseminated to communities of interest?**

1) Primary means of disseminating results has been through conference, workshop, presentations, and journal publications

2) Project website (http://www3.nd.edu/~lemmon/projects/NSF-08-611/) provides another way of spreading information about the project.

*** What do you plan to do during the next reporting period to accomplish the goals?**

Plans for the next reporting period are to 1) complete publications and work regarding real-time scheduling in networked control systems, and 2) complete publications and work regarding controlling the effective bandwidth of networked systems.

Products

Journals

Q. Ling and M.D. Lemmon (2010). A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise. *IEEE Transactions on Automatic Control*. 55 (11), 2590.

Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Q. Ling, M.D. Lemmon, and H. Lin (2010). Asymptotic stabilization of dynamically quantized nonlinear systems in feedforward form. *Journal of Control Theory and Applications*. 8 (1), 27.

Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

J. Yi, C. Poellabauer, X.S. Hu and L. Zhang (2011). Minimum Bandwith Reservaations for Periodic Streams in Wireless Real-time systems. *IEEE Transactions on Mobile Computing*. 10 (5), 479.

Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Lichun Li and M.D. Lemmon (2013). Computational synthesis of event-triggers for MMSE state estimators with communication constraints. *IEEE Transactions on Control Systems Technology*. .

Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

J. Yi, C. Poellabauer, X.S. Hu, T. Chantem and L. Zhang (2010). Dynamic Channel Reservations for Wireless Multihop Communications. *Mobile Computing and Communications Review*. 14 (3), .

Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Books

Book Chapters

Thesis/Dissertations

Pu Wan. *Event-triggered distributed algorithms for network optimization*. (2009). University of Notre Dame.

Acknowledgment of Federal Support = Yes

T. Chantem. *Real-time System Design under Physical and Resource Constraints*. (2011). University of Notre Dame.

Acknowledgment of Federal Support = Yes

Conference Papers and Presentations

Q. Ling and M.D. Lemmon (2010). *Input-to-state stabilization of quantized linear control systems under dropouts*. American Control Conference. Baltimore.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Shengyan Hong, Xiaobo Hu, and M.D. Lemmon (2010). *An adaptive approach to reduce control delay variations*. Real-time Systems Symposium. Washington DC.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

S. Hong, X.S. Hu, and M.D. Lemmon (2010). *Reducing Delay Jitter of Real-time Control Tasks through Adaptive Deadline Adjustments*. Euromicro Conference on Real-time Systems (ECRTS10). Brussels, Belgium.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

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

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

S. Hong, X.S. Hu and M.D. Lemmon (2011). *An adaptive transmission rate control approach to minimize energy consumption*. IEEE Real-time and Embedded Technology and Applications Symposium. Chicago IL, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

S. Hong, T. Chantem, and X.S. Hu (2011). *Meeting end-toend deadlines through distributed local assignment*. IEEE Real-time and Embedded Technology and Applications. Chicago, IL, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Xia and M.D. Lemmon (2011). *Event-triggered network Utility Maximization through Consensus Filtering*. IEEE Conference on Decision and Control. Orlando, Florida, UA.

Status = SUBMITTED; Acknowledgement of Federal Support = Yes

T. Chantem, J. Yi, S. Hong, X.S. Hu, C. Poellabauer, and L. Zhang (2011). *An online holistic scheduling framework for energy-constrained wireless real-time systems*. IEEE International Conference on Embedded and Real-time Computing Systems and Applications. Toyama, Japan.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

S. Hong, T. Chantem, and X.S Hu (2011). *Meeting end-to-end deadlines through distributed local deadline assignment*. IEEE Real-time Systems Symposium (RTSS). Vienna, Austria.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Lichun Li, Bin Hu, and M.D. Lemmon (2012). *Resilient Event-triggered Systems with Limited Communication*. IEEE Conference on Decision and Control. Hawaii, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

X.S. Hu, S. Hong, and M.D. Lemmon (2012). *Supporting Coordinated Negotiation in CPS Design*. International Conference on Cyber-Physical Systems. Beijing, China.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M.D. Lemmon (2012). *Towards a Passivity Framework for Power Control and Response Time Management in Cloud Computing*. International Workshop on Feedback Computing. San Jose, CA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Z. Wang, M. Xia, and M.D. Lemmon (2013). *Voltage stability of weak power distribution networks with inverter connected sources*. American Control Conference. Washington DC.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Bin Hu and M.D. Lemmon (2013). *Using Channel State Feedback to Achieve Resilience to Deep Fades in Wireless Networked Control Systems*. Conference on High Confidence Networked Systems. Philadelphia, PA, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Publications
M.D. Lemmon (2011). *Performance of networked Control Systems under Sporadic Feedback*. invited presentation at KTH, Stockholm, Sweden.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Technologies or Techniques
Nothing to report.

Patents
Nothing to report.

Inventions
Nothing to report.

Licenses
Nothing to report.

Websites

Title:	CPS:Small:Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network
URL:	http://www3.nd.edu/~lemmon/projects/NSF-08-611/
Description:	project's website

Other Products
Nothing to report.

Participants

Research Experience for Undergraduates (REU) funding

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Shengyan Hong	Graduate Student (research assistant)	12
Jie Liu	Graduate Student (research assistant)	3
Meng Xia	Graduate Student (research assistant)	12
Lichun Liu	Graduate Student (research assistant)	6
Zhao Wang	Graduate Student (research assistant)	2
Bin Hu	Graduate Student (research assistant)	12

Michael D Lemmon	PD/PI	3
Xiaobo S Hu	Co PD/PI	2
Pu Wang	Graduate Student (research assistant)	2
Tam Chantem	Graduate Student (research assistant)	2
Mingming Cai	Graduate Student (research assistant)	9

What other organizations have been involved as partners?

Name	Location
EmNet LLC	South Bend Indiana
Odyssian Technology	South Bend Indiana

Have other collaborators or contacts been involved? Y

Impacts

What is the impact on the development of the principal discipline(s) of the project?

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 are itemized below.

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

2) Firm real-time quality-of-service (QoS) constraints provide a realistic method for assuring the closed-loop control system's performance (control systems and real-time systems)

3) Reservation based access provides a more effective way of achieving real-time guarantees than contention based access in wireless networks (real-time systems and wireless networking)

4) Exponentially bursty models of dropouts allow one to use the network calclus to assess the impact that end-to-end QoS has on a wireless networked control systems' performance and stability

5) This project provided one of the first systematic studies of the impact quantization has in event-triggered control systems

6) Development of a passivity framework for power and response time management in networked systems

7) Development of holistic scheduling framework for energy-constrained wirelss real-time systems.

What is the impact on other disciplines?

This project's finding have contributed to power system applications. The PI has collaborated with a small business (Odyssian LLC) to develop wireless networks for economic dispatch of 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 embedded wireless sensor networks is part of a joint project with Notre Dame's biology department to develop novel monitoring methods for tracking nutrient loading across a watershed.

The project's PI has collaborated with S. Rafiliu and P. Eles (Linkoping University) to study the use of stability concepts in computing.

The project's PI and students (Z. Wang) have worked with General Electric and Accenture to develop distributed dispatch algorithms for low-voltage microgrids.

What is the impact on the development of human resources?

Contributions to Human Resource Development are listed below:

1) Training of graduate students: S. Hong, J. Liu, M. Xia, T. Chantem, Lichun Li, Z. Wang, and Mingming Cai

2) Development and web dissemination of course material for graduate course in CyberPhysical 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, P. Wan, J. Yi, Lichun Li)

What is the impact on physical resources that form infrastructure?
Nothing to report.

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

Changes

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.