Preview of Award 1239222 - Annual Project Report

Cover

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Project Title:	CPS: Synergy: Resilient Wireless Sensor-Actuator Networks
PD/PI Name:	Michael D Lemmon, Principal Investigator J. Nicholas Laneman, Co-Principal Investigator Hai Lin, Co-Principal Investigator
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
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Reporting Period:	10/01/2012 - 09/30/2013
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) are systems consisting of numerous sensing and actuation devices that interact with the environment and coordinate their activities over a wireless communication network. WSANs represent an important class of cyber-physical system (CPS) found in the national power grid and air/traffic networks.

This project addresses the issue of resilience in WSANs. A resilient system is one that maintains an active awareness of surrounding threats and reacts to those threats in a manner that returns the system to operational normalcy in finite time. It has proven challenging to ensure resilience in large-scale WSANs because of the complexity such scale brings. This project's approach rests on two fundamental trends that have the potential to transform the way we manage CPS. One trend concerns the revolution in machine-to-machine (M2M) communication networks that promise wireless networking with greater peak bit-rates and reliability than previously possible. Another trend concerns recent results that take advantage of the information transported over the physical component of a CPS to dramatically reduce the bit-rates required across the wireless channel. These results are based on recent advances that treat quantization and event-triggered feedback in a unified manner. By integrating these innovations from controls and communications into a layered and distributed control architecture that is characteristic of many intelligent control systems, the systems developed in this project promise an unprecedented level of resilience to transient and crash faults.

The project will evaluate and demonstrate this integrated control/communication approach to resilience on a multi-robotic testbed consisting of both unmanned ground and aerial vehicles. The testbed integrates M2M communication wireless networking hardware/software with a resilient multi-robot control architecture addressing both task coordination and platform

stabilization.

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

Major Activities: Major Activities for period 8/31/2012 - 9/1/2013

1) Acquistion and installation of RGBD OptiTrak motion capture system to serve as indoor GPS for multi-robot testbed

2) Acquisition and initial testing of ground robotic testbed. Current testbed uses three Pioneer mobile robots that currently communicate using a traditional sockets interface over a wireless LAN. Position of vehicles are tracked using the OptiTrak motion capture system. This testbed is being used to experimentally evaluate the resilience of leader-follower formation control to deep fades in the communication network.

3) Selection and initial testing of aerial unmanned vehicle and integration of these AUV with the OptiTrak motion capture system.

4) Selection and initial testing M2M radio module components. The module is based on a gumstix processor with embedded 802.11g compliant radio module.

5) Research work into resilient coordination and control of groups of mobile robots based on hybrid systems theory and supervisory control theory. In particular, a hierarchical control structure is introduced that uses a discrete-event supervisor on the top layer providing logical commands to a low-level regulation (control) layer that directly interacts with the physical robot. The interface between the supervisory and regulation layers is based on a partition of the motion space of robots into logically equivalent regions. This partition generates a bi-simular quotient transition system is derived and utilized by the top layer to design supervisors.

6) Research work on the resilience of wireless sensor-acutator networks to deep fades in the communication channel. In particular, this work models the channel fades using an exponential bounded burstiness (EBB) model from which it is possible to develop switched control architectures assuing the almost sure practical stability of the system. These methods are applied to leader-follower formation control in the project's mobile robotic testbed.

7) Research work investigating communication algorithms for the sporadic traffic generated by event-triggered messaging systems. In particular, we are looking closely at orthogonal-frequency division multiplex (OFDM) physical layers, which are prevalent and seen immense commercial development for both cellular telecommunications, e.g., 3GPP LTE, and wireless local area networks, e.g., IEEE 802.11, and are increasingly targeting machine-to-machine (M2M) applications. The objective is not only to leverage these technologies to the fullest extent but develop around them appropriate (lightweight) link, multi-access, routing, and discovery services appropriate to event-triggered networked control.

Specific Objectives: Specific objectives for the period from 8/31/12-9/1/13

1) Development of mobile ground robot testbed using wireless communication to coordinate robot activities.

2) Development of aerial robotic tesbed using wireless communication to coordinate robot activities

3) Development of an M2M communication module for use in the robotic testbeds

4) Development of control algorithms that adapt to deep fades in the communication network

Significant Results:

Significant Results for reporting period 8/31/2012-9/1/2013

1) The project completed the establishment of the Distributed Cooperative Systems Research (DISCOVER) Lab. The lab is located at B29 Fitzpatrick Engineering Hall, University of Notre Dame. The testbed consists of both autonomous unmanned ground (UGV) and aerial vehicles (UAVs) together with a 24-camera OptiTrak motion capture system that provides indoor localization information.

2) Leader-follower control algorithms have been designed for the mobile ground robots that are resilient to deep fades in the communication network.

3) The project selected and acquiared of robust quadrotor platform and has begun initial flight testing of the quadrotor in the DISCOVER lab. The supplier is a group out of UIUC connected to Hovakimyan's group. The quadrotors use an L1-adaptive controller thereby providing an exceptionally stable platform on which to develop the supervisory controls.

4) The project the beginnings of a commercially-oriented M2M module based on the Gumstix devices with embedded IEEE 802.11g (WiFi). The devices have been successfully tested with the DISCOVER lab's ground robot testbed. We believe there will be hardware and software upgrades required to support the UAV testbed specifically and resilient WSAN applications more generally. Specifically, we anticipate upgrading the oscillators, moving to the IEEE 802.11ah standard as soon as development boards become available, and replacing TCP/IP with lightweight discovery, multi-access, and routing protocols.

Key outcomes or Other achievements:

Key outcomes and other achievements for reporting period 8/31/2012-9/1/2013

- Dr. Laneman's group has developed point-to-point and multi-access models for intermittent communication, in which some mechanism causes the transmissions to be randomly dispersed in time in an ON/OFF fashion. Examples of intermittency could be in the message arrivals, e.g., event-triggered control, or channel access, e.g., carrier sensing or cognitive radio. We have explored achievable rates for a variety of decoding approaches that blend identifying the locations of the transmissions and decoding the messages. In particular, the larger achievable rate (regions) are obtained when we jointly search for transmissions and decode messages, and we have introduced a new information theoretic quantity called the "partial divergence" to obtain certain exponential bounds on error probabilities and therefore communication rates.

- Dr. Laneman's group has established an achievable rate region for Gaussian multiple access channels with delay, or blocklength, constraints. This region allows system designers to understand the fundamental tradeoffs among rates and reliabilities of multiple users communicating to a common receiver, and provides a benchmark for

evaluation of protocol designs. Among other insights, the region demonstrates that time-sharing, i.e., diving the channel up into orthogonal time or frequency slots, has a greater penalty in terms of sum-rate when taking into account delay constraints than the capacity region would suggest.

- Frequency-shift keying (FSK) is traditionally considered a practical and energy-efficient modulation format for sensor-actuator networks. Dr. Laneman's group is exploring how to mimic FSK modulations using a OFDM physical layer, and how to creating coding schemes that can offer higher data rates and therefore better tradeoffs between power- and bandwidth-efficiency.

- Experimentally, Dr. Laneman's group has developed an embedded M2M networking testbed using the Gumstix platform (https://www.gumstix.com), which include an ARM processor, an IEEE 802.11 (WiFi) module, and USB and other interfaces for extensibility. ARM processors were selected to be compatible with the DISCOVER lab's quadrotors. Of note is that the integrated IEEE 802.11g module supports data rates up to 1.5 MBps, whereas the standard specifies modulation and coding rates up to 6.75 MBps, suggesting that it is important to take into account the embedded implementation and protocol overhead from higher layers. Nevertheless, these data rates are significantly higher than the predominant IEEE 802.15.3 (ZigBee) wireless modules. Commercially, there is a significant amount of momentum behind extending IEEE 802.11-based standards to support M2M, specifically the evolving IEEE 802.11ah standard. We will be bringing the experimental Gumstix testbed.

- Dr. Lemmon's developed and tested a method for assuring the resilience of quantized event-triggered systems to abrupt impulsive disturbances. Quantized feedback systems require the communication link's encoder and decoder to have sychronized codebooks. This sychronization is broken if an impulsive disturbance of unknown magnitude hits the physical system. The methods developed in this work show how quickly one can resynchronize the codebooks and thereby return the disturbed system back to its nominal operating level.

- Dr. Lemmon's has developed methods that assure almost sure practical stability of leader follower formation control of nonholonomic ground robots. One issue in such systems is when a deep fade between the leader and follower makes it impossible for the follower to adequately anticipate the leader's future movements. This work uses an exponentially bounded burstiness (EBB) model for channel fading and shows how knowledge of this model along with real-time measurements of the channel state can be used to assure the almost-sure practical stability of leader following. Current work has tested this idea on a detailed simulation model of the ground robot testbed. Future work will implement the method in the DISCOVER lab's ground robot testbed first using XBee radio modules and later M2M 802.11 radio modules.

- While this project primary focus is on formation control and task coordination in multi-robot testbeds, many of the principles can be applied to other applications. Dr. Lemmon's group has done a preliminary exmination of resilient control concept for two other applications; the first involving the use of passivity concept for resilient control of cloud computing systems and the second looking at resilient control of electrical microgrids.

- Dr. Lemmon and Lin's group worked together to develop an interface model

describing the way the resilient "control" algorithms view the communication network. The interface is a high-level specification about which control algorithm development and M2M networking software can be succesfully co-developed.

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

1) Work with the project testbed has provided numerous opportunities for students to work directly with embedded computing systems

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

1) Primary means of disseminating the results has been through conferences and workshops.

2) Our sponsorship of this year's midwest control and game theory workshop (WCGT-2013) at the University of Notre Dame (April 26-27,2013) was instrumental in identifying a supplier for the lab's quadrotors.

3) Project website (http://www3.nd.edu/~lemmon/projects/NSF-12-520/) provides a passive way of information dissemination.

4) The project has worked through Notre Dame's and the Wireless Institute's press offices to more broadly disseminate the announcement of this project to Notre Dame and its network of alumni.

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

Proposed project goals for the next reporting period (8/31/2013-9/1/2014)

1) Complete development of prototype M2M 802.11 communication module.

2) Complete hardware testing of resilient leader-follower algorithms on the DISCOVER lab's ground robot testbed.

3) Begin the comparison of the suitability of XBee and 802.11 communication technologies for the support of resilient networked control systems.

4) Complete initial testing of coordinated formation control algorithms in the DISCOVER lab's quadrotor testbed.

Products

Journals

Lichun 'Lucinda' 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

A. Karimoddini, H. Lin, B.M. Chen, and T.H. Lee (2013). A bumpless hybrid supervisory control algorithm for the formation of unmanned helicopters. *Mechatronics*. .

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

A. Karimoddini, H. Lin, X. Dong, F. Lin, G. Cai, B.M. Chen, and T.H. Lee (2013). Hybrid modeling and control of the regulation layer of unmanned helicopter. *International Journal of Control*. .

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

Books

Book Chapters

Thesis/Dissertations

Conference Papers and Presentations

M.D. Lemmon (2012). *Towards a passivity framework for power control and response time management in cloud computing*. 7th international workshop on feedback computing. San, Jose, CA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Lichun 'Lucinda' Li, Bin Hu, and M.D. Lemmon (2012). *Resilient event triggered systems with limited communication*. IEEE Conference on Decision and Control. Maui, Hawaii, USA.

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 D.C., USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Lichun 'Lucinda' Li, M.D. Lemmon (2013). *Polynomial approximations of optimal event triggers for state estimation problems using SOSTOOLS*. American Control Conference. Washington D.C., USA.

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

A. Karimoddini, H. Lin, B.M. Chen, and T.H. Lee (2013). *A smooth hybrid symbolic control for a team of UAVs over a partitioned space*. American Control Conference. Washington D.C., USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

A. Karimoddini and H. Lin (2013). *Hierarchical Hybrid Symbolic Control for Robot Motion Planning*. Proc. of 10th IEEE International Conference on Control and Automation. P.R. China.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Khoshnevisan and J. Nicholas Laneman (2013). *Intermittent Multi-Access Communication: achievable rates*. IEEE International Symposium on Information Theory. Istanbul, Turkey.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Khoshnevisan and J. Nicholas Laneman (2013). *Upper Bounds on the Capacity of Binary Intermittent Communication*. Workshop on Information Theory and Applications. Univ. of California, San Diego, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

E. MolavianJazi and J. Nicholas Laneman (2012). *Simpler Achievable Rate Regions for Multi-access with Finite Blocklength*. IEEE Int. Symp. Information Theory. Boston, MA, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Khoshnevisan and J. Nicholas Laneman (2013). *Achievable Rates for Intermittent Communication*. IEEE Int. Symp. Information Theory. Boston, MA, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Khoshnevisan and J. Nicholas Laneman (2012). *intermittent Communication and Partial Divergence*. Allerton Conf. Communications, Control, and Computing. Monticello, IL, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

E. MolavianJazi and J. Nicholas Laneman (2012). *A random coding approach to Gaussian multiple access channels with finite block length*. Allerton Conf. Communications, Control, and Computing. Monticello, IL, USA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Publications

Technologies or Techniques
Nothing to report.

Patents
Nothing to report.

Inventions
Nothing to report.

Licenses
Nothing to report.

Websites

Title: CPS: Synergy: Resilient Wireless Sensor-Actuator Networks
URL: http://www3.nd.edu/~lemmon/projects/NSF-12-520/
Description: Project 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
Bin Hu	Graduate Student (research assistant)	12
Mostafa Khoshnevisan	Graduate Student (research assistant)	9
Ebrahim MolavianJazi	Graduate Student (research assistant)	3

Hai Lin	Co PD/PI	1
J. Nicholas Laneman	Co PD/PI	1
Michael D Lemmon	PD/PI	1
Sahand Golnarian	Graduate Student (research assistant)	3
Alireza Partovi	Graduate Student (research assistant)	9
Jin Dai	Graduate Student (research assistant)	6
Bo Wu	Graduate Student (research assistant)	12
Ali Karimoddini	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Xiaobin Zhang	Graduate Student (research assistant)	12

What other organizations have been involved as partners?
Nothing to report.

Have other collaborators or contacts been involved? N

Impacts

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

The project's results will generate the following impacts on control theory and communication systems.

1) The adoption of a sporadic event-triggered approach to control provides a way of generating control applications that are inherently resilient to variations in the communication network's quality of service. This will have a great impact on networked control systems that rely on wireless communication networks for coordination and control.

2) The project's sporadic event-triggered communication model provides a richer set of assumptions than is usually assumed in classical information theory. The outcomes of this project, therefore, may have a great impact on classical information theory in its focus on latency, sporadic events, and the tight coupling between transmitter and receiver data streams.

3) The project's focus on multi-robotic testbeds will impact applications in vehicle-to-vehicle control, communication as well as coordinated management of swarms of umanned air vehicles.

What is the impact on other disciplines?

The project's original application focuses on multi-robotic systems. But the ideas inherent in this project are also applicable to other applications. In particular, recent conversations with a microgrid group at Aalborg University may provide an avenue to extending this project's impact to the control of electrical power systems.

What is the impact on the development of human resources?
Nothing to report.

What is the impact on physical resources that form infrastructure?

This project has developed a major multi-robot lab facility (DISCOVER lab) at the University of Notre Dame. This facility is serving to attract new students to the program as well as additional colllaborative efforts.

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?

The project has already attracted the interest (through the ND's wireless institute) of Intel and Qualcomm in the project's use of M2M technologies. Based on preliminary conversations with these groups, it is possible this project will have on impact on the commercial technologies of these companies.

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.