Preview of Award 1239222 - Annual Project Report

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1239222
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
Recipient Organization:	University of Notre Dame
Project/Grant Period:	10/01/2012 - 09/30/2015
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Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
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:

1) Graduate student Bin Hu working under the direction of Dr. Lemmon completed development of a novel framework for almost sure asymptotic safety in vehicular networks. This work developed control architectures that ensure that the probability of vehicular accidents asymptotically goes to zero in the absence of any catastrophic event. This guarantee is provided even when the vehicular network's wireless channel exhibits deep fades (outages). Mr. Hu also used this safety concept to develop novel event-triggered transmission schemes that ensure asymptotic safety while greatly reducing the amount of channel bandwidth required by the system. Mr. Hu is currently working to implement these algorithms on the DISCOVER lab's ground vehicles to obtain a hardware demonstration of the approach by the end of summer 2014.

2) Graduate student Tua Tamba working under the direction of Dr. Lemmon has developed a framework for forecasting critical transitions (regime shifts) in networked dynamical systems that can be modeled using polynomial vector fields. This work provided two new results. The first result provided algorithms that used semidefinite programming (SDP) relaxations to solve stochastic reachability problems for processes subject to jump disturbances. The second result used hierarchies of (SDP) relaxations and some novel concepts from algebraic geometry to obtain lower bounds on the minimum distance-to-bifurcation (a.k.a. inverse bifurcation problem) for systems with multi-parametric uncertainties. Both methods were primarily tested on examples assessing the resilience of ecological systems to environmental change. We are currently studying to see how these ideas can be used in the vehicular network applications of this particular project.

3) Graduate Sahand Golnarian, working with Dr. Laneman, continued to develop a machine-to-machine communications capability based upon the Gumstix platform and IEEE 802.11n USB adaptors. Software was written to generate information packets of varying lengths, to transmit them with and without retransmissions between two Gumstix nodes, and to calculate statistics on packet loss rate, packet loss temporal correlations, throughputs, and delays. With this capability, the graduate student and an undergraduate student began characterizing a robot-to-robot communication link as a function of separation distance in both indoor and outdoor settings. As we continue to characterize these communication links for the purpose of contributing to the team’s effort of building a resilient WSAN application programming interface (API), we will be conducting measurements to characterize performance when multiple wireless devices need to share the medium. We also plan to complement the existing Gumstix + WiFi wireless capability with a software-defined radio (SDR) capability (Ettus Research B210), which will allow even more adaptivity of the physical layer and other cross-layer aspects of the communication links.

4) Graduate student Mostafa Khoshnevisan, working with Dr. Laneman, continued to develop models and fundamental limits for intermittent communications. In the past year, work focused on developing several related models for multiaccess channels with intermittency, modeling bursty sources, collisions, or a sporadic channel availability such that the receiver does not know a priori when transmissions will occur. We also refined this students’ work into a journal submission, and he completed his PhD dissertation. For this purposes of this project, this line of work is considered complete.

5) Graduate student Ebrahim MolavianJazi, working with Dr. Laneman, continued to

develop an understanding on the tradeoffs among rate, reliability, and latency of block codes in finite blocklength information theory. A unified framework was developed for treating Gaussian channels with power constraints. This framework was extended over the course of the past year to treat slow fading Gaussian channels and to identify significant costs of time-sharing when channel uses are precious. We also refined this student's earlier work on the Gaussian multiaccess channel into a journal submission, and he completed his PhD dissertation. For the purposes of this project, this line of work is considered complete.

6) Graduate student A. Partovi working with Dr. Lin, investigated the task decomposition problem of multi-agent systems. Task decomposition among agents refers to a process to decompose a given global task into subtasks for individual agents. The decomposition is not arbitrary and should be done in such a way that the satisfaction of the sub-tasks by all agents individually would imply the accomplishment of the global task collectively. In this paper, it is assumed that agents are modeled by labeled transition systems, and the global specification is given as a subclass of Computation Tree Logic (CTL) formulas. It is also assumed that the global CTL specification is broadcasted to and known by all agents. Agents could be heterogeneous and have different capabilities. In order to obtain subtasks for each agent with a maximum potential for fault tolerance, the basic idea is to let each agent contribute to their maximum capabilities in the sense of satisfying a maximum number of sub-formulas of the global specification. The maximum satisfaction set is achieved through a modified CTL model checking algorithm. These maximum satisfiable sub-formulas can be used as the subtask for the corresponding agent. Furthermore, based on assume-guarantee reasoning, sufficient conditions are derived to guarantee the satisfaction of the global CTL specification provided that each agent fullfill its own subtasks.

7) Former graduate student A. Karimoddini, working with Dr. Lin implemented the top-design approach for the coordination of unmanned helicopters using a conic partition of the fly zone. In particular, a decentralized hybrid supervisory control approach was used for two unmanned helicopters that are involved in a leader-follower formation mission. Using a polar partitioning technique, the motion dynamics of the follower helicopters are abstracted to finite state machines. Then, a discrete supervisor is designed in a modular way for different components of the formation mission. Furthermore, a formal technique is developed to design the local supervisors in a decentralized manner, so that the team of helicopters as a whole can cooperatively accomplish a collision-free formation task.

8) Graduate Student Dai Jin, working with Dr. Lin, focused on the development of automatic task decomposition and supervisor syntehsis methods based on a combination of methods from superivsory control, regular inference, and model checking. Along this line, they have made progress in the problem of automatic synthesis of decentralized supervisor synthesis for uncertain discrete event systems was considered. To deal with the unknown plants, the co-normality of prefix-closed regular languages were studied and formulas for computing the supremal co-normal sublanguages were proposed; then sufficient conditions for the existence of decentralized supervisors were given in terms of language controllability and co-normality and a learning-based algorithm to synthesize the supervisor automatically is proposed. Moreover, the paper also studies the on-line decentralized supervisory control of concurrent discrete event systems that are composed of multiple interacting unknown modules. The concept of modular controllability is employed to characterize the necessary and sufficient conditions for the existence of the local supervisors, which consist of a set of local supervisor modules, one for each plant module and which

determines its control actions based on the locally observed behaviors, and an on-line learning-based local synthesis algorithm is also presented.

Specific Objectives: Specific objectives for this year's work were to

1) continue development of asymptotic safety concepts and integrate those concepts and controller algorithms into the project's multi-robotic testbed

2) continue development of M2M communication module for eventual integration into the multi-robotic testbed

3) continue developmentof multi-robotic testbed to provide resilient coordination between the testbed's gound and air vehicles.

Significant Results: Significant accomplishments are

1) Dr. Lemmon and his student (B. Hu) completed analytical work on asymptotic safety in multi-robotic task coordination which led to the submission of a journal paper (Distributed Switching Control to Achieve Almost Sure Safety for Leader-Follower Nonholonomic Systems, submitted to IEEE Transactions on Automatic Control, February 2014.)

2) Dr. Lemmon and his student (T. Tamba) completed work studying the resilience of networked systems to jump disturbances as a stochastic reachability problem. This work led to the submission of a journal paper (T.A. Tamba and M.D. Lemmon (2014), Stochastic Reachability of Jump-Diffusion Process using Sum of Squares Optimization, submitted to IEEE Transactions on Automatic Control, June 2014).

3) Dr. Laneman and his student (M. Khoshnevisan) completed work on Intermittent communication and on Gaussian channels with power constraints. This led to the submission of a journal paper (M. Khoshnevisan and J. N. Laneman, “Intermittent Communication,” IEEE Trans. Inform. Theory, Jan. 2014, submitted for publication) and graduation of one PhD student (M. Khoshnevisan, “Intermittent Communication,” Ph.D. dissertation, University of Notre Dame, Notre Dame, IN, Jan. 2014)

4) Dr. Laneman and his student (E. MolavianJazi) completd work on Guassian channels with power constraints. This work led to the submission of a journal paper (E. MolavianJazi and J. N. Laneman, “A Finite-Blocklength Perspective on Gaussian Multi-Access Channels,” IEEE Trans. Inform. Theory, Mar. 2014, submitted for publication) and the graduation of a PhD student (E. MolavianJazi, “A Unified Approach to Gaussian Channels with Finite Blocklength,” Ph.D. dissertation, University of Notre Dame, Notre Dame, IN, Aug. 2014.)

4) Dr. Lin and his student (J. Dai) completed development of a novel learning-based approach to decentralized supervisory control. This led to an accepted Journal Paper (J. Dai and H. Lin, ``A Learning-based Synthesis Approach to Decentralized Supervisory Control of Discrete Event Systems with Unknown Plants," accepted by Control Theory and Technology, 2014.)

5) Dr. Lin and his student (A. Karimoddini) completed work implementing a decentralized hybrid supervisory control approach for leader-follower formation control of two robots. This work led to a published conference paper (A. Karimoddini, M. Karimadini, and H. Lin, ``Decentralized hybrid formation control of unmanned aerial vehicles," in Proc. of the 2014 American Control Conference, Portland, OR, June 4-6, 2014)

Key outcomes or Other achievements:	Key outcomes this year included the publication/submission of several journal papers and the graduation of two PhD students.

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

This project provided research training opportunities for a number of graduated students; Sahand Golnarian, Mostafa Khoshnevisan, Ebrahim MolavianJazi, Tua Tamba, Bin Hu, Xiaobin Zhang, Bo Wu, Dai Jin, and Alireza Partovi. The project graduated two PhD students (Ebrahim MolavianJazi and M. Khoshnevisan). One graduate student completed his PhD proposal (T. Tamba). All students have completed their initial qualifying exams.

This project provided opportunities for 4 undergraduate students (T. Luppi, J. Driano, M. Biggins, and S-G Kang) to work on projects related to the DISCOVER lab and the development of the M2M communication module.

This project provided internship opportunities for 1 high school student (L. Gong).

Project's Co-PI (Lin) and his graduate students participated in an outreach effort (Notre Dame Robotic week) to high school and K-12 teachers.

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

Research results have been disseminated through conference presentations as well as invited presentations at select Universities.

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

Plans for next year are

1) complete demonstration of asymptotic safety work on mobile robot testbed (Lemmon and B. Hu)

2) complete demonstration of Dr. Lin's parallel task decomposition work on the mobile robot testbed

3) integration of software defined radio M2M communication module into the robotic testbed (Laneman and S. Golnarian)

Products

Books

Book Chapters

Conference Papers and Presentations

A. Partovi and H. Lin (2014). *Assume-guaranteed cooperative satisfaction*. Proceedings of the 2014 American Control Conference. Portland, OR. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

A. Karimoddini, M. Karimadini, and H. Lin (2014). *Decentralized hybrid formation control of unmanned aerial vehicles*. Proc. of the 2014 American Control Conference. Portland, OR. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

J. Dai and H. Lin (2014). *Decentralized supervisory control of discrete event systems with unknown plants: a learning-based synthesis approach*. Proc. of the 11th IEEE International Conference on Control and Automation. Taichung, Taiwan. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Bin Hu and M.D. Lemmon (2014). *Distributed switched supervisory control to achieve almost sure safety for a class of interconnected networked systems*. IEEE International Conference on Control and Automation (ICCA). Taichung, Taiwan. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Bin Hu and M.D. Lemmon (2014). *Distributed switching control to achieve resilience to deep fades in leader-follower nonholonomic systems*. Conference on High Confidence Networked Systems (HiCoNS). Berlin, Germany. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

T.A. Tamba and M.D. Lemmon (2014). *Forecasting the Resilience of Networked Dynamical Systems under Environmental Perturbations*. Conference on High Confidence Networked Systems (HiCoNS) work-in-progress session. Berlin, Germany. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

E. MolavianJazi and J.N. Laneman (2013). *On the second-order coding rate of non-ergodic fading channels*. Proceedings of Allerton Conference on Communications, Control and Computing. Monticello, IL. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

B. Wu, H. Lin, and M.D. Lemmon (2014). *Stability analysis for wireless networked control systems in un-slotted IEEE 802.15.4 protocol*. Proc. of the 11th IEEE International Conference on Control and Automation. Taichung, Taiwan. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

T.A. Tamba and M.D. Lemmon (2014). *The distance-to-bifurcation problem in non-negative dynamical systems with kinetic realizations*. IEEE International Conference on Control and Automation (ICCA). Taichung, Taiwan. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

T.A. Tamba and M.D. Lemmon (2014). *Using first passage times to manage eco-system regime shifts*. IEEE Conference on Decision and Control. Florence, Italy. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Journals

A. Karimoddini and H. Lin (2014). Hierarchical hybrid symbolic robot motion planning and control. *Asian Journal of Control*. . Status = ACCEPTED; 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*. 23 (6), 677. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.mechatronics.2013.07.004

A. Karimoddini, H. Lin, X. Dong, F. Lin, G. Cai, B.M. Chen, and T.H. Lee (2013). Hierarchical hybrid modeling and control of an unmanned helicopter. *International Journal of Control*. 87 (9), 1779. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: DOI:10.1080/00207179.2014.889853

Bin Hu and M.D. Lemmon (2014). Distributed Switching Control to Achieve Almost Sure Safety for Leader-Follower Nonholonomic Systems. *IEEE Transactions on Automatic Control*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

E. MolavianJazi and J.N. Laneman (). A finite-blocklength perspective on Gaussian multi-access channels. *IEEE Transactions on Information Theory*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

H. Lin (2014). Mission Accomplished: an introduction to formal methods in mobile robot motion planning and control. *Unmanned Systems*. 2 (2), 201. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1142/S2301385014300029

H. Lin and P.J. Antsaklis (2014). Hybrid Dynamical Systems: an introduction to control and verification. *Foundations and Trends in Systems and Control*. 1 (1), 1. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1561/2600000001

J. Dai and H. Lin (2014). A learning-based synthesis approach to decentralized supervisory control of discrete event systems with unknown plants. *Control Theory and Technology*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

M. Khoshnevisan and J.N. Laneman (2014). Intermittent Communication. *IEEE Transactions on Information Theory*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

T.A. Tamba and M.D. Lemmon (2014). Stochastic Reachability of Jump-Diffusion Process using Sum of Squares Optimization. *IEEE Transactions on Automatic Control*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

X. Liu, H. Lin and B.M. Chen (2013). Structural controllability of switched linear systems. *Automatica*. 49 (12), 3531. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.automatica.2013.09.015

Licenses

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

M. Khoshnevisan. *Intermittent Communication*. (2014). University of Notre Dame. Acknowledgement of Federal Support = No

Websites

CPS: Synergy: Resilient Wireless Sensor-Actuator Networks
http://www3.nd.edu/~lemmon/projects/NSF-12-520/

project's website - access to all project publications and videos, course websites, and internal project meeting documents. (password 'vault')

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Lemmon, Michael	PD/PI	1
Laneman, J. Nicholas	Co PD/PI	1
Lin, Hai	Co PD/PI	1
Dai, Jin	Graduate Student (research assistant)	12
Golnarian, Sahand	Graduate Student (research assistant)	12
Hawn, Derek	Graduate Student (research assistant)	3
Hu, Bin	Graduate Student (research assistant)	9
Khoshnevisan, Mostafa	Graduate Student (research assistant)	6
MolavianJazi, Ebrahim	Graduate Student (research assistant)	6

Partovi, Alireza	Graduate Student (research assistant)	3
Tamba, Tua	Graduate Student (research assistant)	1
Wu, Bo	Graduate Student (research assistant)	12
Zhang, Xiaobin	Graduate Student (research assistant)	6

Full details of individuals who have worked on the project:

Michael D Lemmon
Email: lemmon@nd.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Principal Investigator - directs a single graduate student working on almost sure stability and resilience of networked control systems.

Funding Support: Department of Electrical Engineering, NSF, and Accenture project

International Collaboration: No
International Travel: Yes, Italy - 0 years, 0 months, 4 days; Germany - 0 years, 0 months, 4 days; Taiwan - 0 years, 0 months, 5 days

J. Nicholas Laneman
Email: jnl@nd.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Participate in project meetings, oversee wireless networking prototyping and experiments, supervise related communications research projects.

Funding Support: None

International Collaboration: No
International Travel: Yes, Spain - 0 years, 0 months, 7 days

Hai Lin
Email: hlin1@nd.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Co-PI - directs 2 students - directs development of project's robotic testbed - research area concerns learning of discrete-event systems and parallel task decomposition

Funding Support: Dept. of EE and NSF

International Collaboration: No
International Travel: No

Jin Dai
Email: jdai1@nd.edu

Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: mobile robot testbed support and learning methods in supervisory control

Funding Support: NSF - CNS 1239222

International Collaboration: No
International Travel: No

Sahand Golnarian
Email: sgolnari@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: graduate student working on reliable and energy-efficient machine-to-machine communication, and our Gumstix testbed

Funding Support: NSF CNS-1239222

International Collaboration: No
International Travel: No

Derek Hawn
Email: dhawn@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: working on development of ground robot demonstration

Funding Support: NSF

International Collaboration: No
International Travel: No

Bin Hu
Email: bhu2@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 9

Contribution to the Project: 1) mobile ground robot testbed development 2) investigate usage of channel state information in vehicle formation control

Funding Support: NSF

International Collaboration: No
International Travel: No

Mostafa Khoshnevisan
Email: mkhoshnevisan@gmail.com
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Mostafa worked on models and fundamental limits for intermittent communication, which is intended to capture bursty sources and / or sporadically available channels.

Funding Support: None

International Collaboration: No
International Travel: No

Ebrahim MolavianJazi
Email: emolavia@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Ebrahim worked on finite blocklength information, exploring fundamental tradeoffs among transmission rate, reliability, and delay.

Funding Support: None

International Collaboration: No
International Travel: No

Alireza Partovi
Email: apartovi@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Second year graduate student studying task coordination in mobile ground robots

Funding Support: NSF CNS-1239222

International Collaboration: No
International Travel: No

Tua Tamba
Email: ttamba@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: investigating relationship between resilience of WSAN and ecological systems.

Funding Support: NSF - Fulbright Fellow

International Collaboration: No
International Travel: No

Bo Wu
Email: bwu3@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: 2nd year student working on intermittent communication and control

Funding Support: NSF - CNS 1239222

International Collaboration: No
International Travel: No

Xiaobin Zhang
Email: xzhang11@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: development of autonomous air vehicle testbed

Funding Support: Dr. Lin's other NSF project

International Collaboration: No
International Travel: No

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

Have other collaborators or contacts been involved? Yes

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, Dr. Lemmon has been working with Notre Dame's department of biological sciences applying resilience concepts developed in this project to the sustainability of aquatic ecosystem services.

What is the impact on the development of human resources?

a. 3 undergraduate students doing research in Discover lab, Spring 2014

Thomas Luppi, Joe Driano and Matthew Biggins,

b. 1 high-school girl, Linda Gong, is doing summer intern in Discover lab, summer 2014

c. Participated the 2014 Notre Dame Robotic week (http://engineering.nd.edu/NDNRW), which is well attended by local kids with parents and k-12 teachers.

d. Seung Goo Kang, a rising junior Electrical Engineering student, joined the M2M Communications Group this summer to help with wireless link performance measurements. We are hopeful that he will continue this coming academic year doing undergraduate research for credit.

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. 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?

As Director of the The Wireless Institute, Dr. Laneman has been developing a Industry/University Cooperative Research Center (I/UCRC) effort to join the Broadband Wireless Access and Applications Center (BWAC) led by the University of Arizona. Committed partners to the Notre Dame IUCRC site include Alcatel-Lucent, InterDigital, National Instruments, Sprint, and the Office of Naval Research. The machine-to-machine wireless communication and cyber-physical systems themes of the present project resonate with several of these committed partners as well as two other potential partners being pursued. As the IUCRC site launches, we will be presenting the results to industry stakeholders for potential parallel or follow-on IUCRC projects.

Dr. Laneman has had discussions with Qualcomm, National Instruments, and AT&T about machine-to-machine communication and cyber-physical systems themes.

What is the impact on society beyond science and technology?

Nothing to report.

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Work on the M2M module was delayed in the first year due to difficulties in identifying qualified students for software and hardware development. This issue was remedied in the second year, but the development of the M2M module is about 1 year behind schedule. The plan to remedy this issue is to put more students (6-7) on the project in year 3 with the objective of integrating a prototype M2M module with the robotic testbed by the project's offcial end date in Sept 2015. If needed, we will request a no-cost extension to finish more in-depth experimental testing of the robotic testbed using the M2M module.

Changes that have a significant impact on expenditures

Since the project employed fewer students in the first year, total expenditures by the end of year 2 (July 31, 2014) on graduate student and faculty salaries were about 75% of the original budget (200k versus 272k). Moreover, since a chipset for the M2M module was not identified until the end of the second year, the technician salary (36k) was not spent in year 2. Finally, the travel budget for the program has been underspent (11k out of 29k) because some faculty used other resources to support most of their foreign travel.

We will address the schedule slip on the M2M module by 1) increasing the number of graduate students (6) supporting this project in the third year, 2) having the technician's support moved to the third year when it is needed, and 3) sending more students on conference travel in the third year.

In May 2014, we asked our sponsored research office to make a projection of the expected balance in Sept 2015 (project's initial end date) based on the preceding spending projections for year 3. The projected balance for Sept 2015 in the salary category was $75k and was $16k for the other direct costs. The plan for this expected balance is to request a no-cost extension at the end of year 3. This will allow us to more completely test the integration of the M2M module with the ground robotic testbed, as well as providing the graduate students more time to finish their journal paper revisions and to write their dissertations.

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.