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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 - 09/30/2016
Reporting Period:	10/01/2014 - 09/30/2015
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 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 Dai Jin, working with Dr. Lin, focused on the issue of fault-tolerance of multi-agent systems. The novelty of the methods comes from the integration of methods from supervisory control, regular inference, and model checking. Modeling the behaviors of each agent in the system as a local automaton and the system behaviors as the composition of them, the fault-tolerance property requires that the system can satisfy a global regular language specification prior to as well as after the occurrence of a fault. In particular, they focused on sensor and actuator failures occurring in individual agents, in which the former are captured as loss of observability of a local event of a failed agent, and the latter are modeled as a total loss of an event from an agent. Should either failure occur, the corresponding local supervisors need to be redesigned and the team needs to be reconfigured as the original task decomposition scheme and controllers would fail to satisfy the specification. For such a pursuit, they propose frameworks for addressing sensor and/or actuator failure tolerance by incorporating a learning-based supervisor synthesis approach and control reconfiguration mechanism in the face of possible failures.

2) Graduate Student Xiaobin Zhang, working with Dr. Lin, investigated the performance guarantee issues for behavior-based robots. Behavior-based robotics (BBR) has gained popularity because of its simplicity, flexibility and adaptability. However, lack of formalization from performance guarantee aspect has been a concern in BBR especially for safety critical applications. Motivated by this challenge, they proposed a formal model for BBR using a discrete-time controlled stochastic hybrid system (dt-cSHS) framework. Uncertainties from sensors, actuators, and the environment were modeled by stochastic kernels in the dt-cSHS. For performance verification, safety and reachability specifications were considered; abstraction and model checking were carried on the hybrid system model.

3) Former graduate student A. Karimoddini, working with Dr. Lin addressed the motion planning problem and proposed a unified hierarchical hybrid control framework using a bismulation-based abstraction technique over the partitioned motion space that can be applied to autonomous aerial robots (3-D symbolic motion planning) or ground vehicles (2-D symbolic motion planning). The bisimulation relation between the abstracted model and the original continuous

system guarantees that their behaviors are the same. This allows to design a discrete supervisor for the abstracted model, and then, the designed supervisor can be applied to the original system while the closed-loop behavior does not change. To apply the discrete supervisor to the original continuous system, an interface layer is developed, which on the one hand translates discrete commands of the supervisor to a continuous form applicable to the continuous plant and on the other hand, abstracts the continuous signals of the continuous low layer to discrete symbols understandable by the supervisor. The proposed algorithm is verified through implementation of a hybrid symbolic algorithm for the formation control of unmanned aerial vehicles.

4) Graduate students Sahand Golnarian and Mingming Cai, working with Dr. Laneman, continued to develop a M2M communications testbed based upon software-defined radio (SDR), with the objective of provided flexibility of the communication protocols all the way down to the phyiscal layer. The testbed was used to evaluate the performance of a flexible SDR implementation of OFDM packet radio transmissions similar to IEEE 802.11n executing on the Ettus Research B210 hardware with the open-source GNU Radio software under various physical layer conditions and statistics on packet loss rate, packet loss temporal correlations, throughput, and delay. The results were compared with those previously obtained using Gumstix and laptop platforms with IEEE 802.11n USB adaptors. The team achieved the desired flexibility with comparable UDP throughput among the platforms; however, the latency of GNU Radio processing on a host laptop was too great for comparable TCP throughput. The latter suggests that more radio functionality must be shifted from host-based processing to dedicated real-time processing on an FPGA.

5) Through parallel NSF funding, Dr. Laneman's team acquired another SDR platform based upon the National Instruments USRP RIO hardware and LabVIEW Communications System Design Software (CSDS) software. This acquisition also includes an FPGA-based implementation of the physical and medium-access layers of 802.11, all of which is modifiable. The team has obtained additional training and suport from National Instruments to effectively integrate this platform into the M2M testbed going forward.

6) Graduate student Sahand Golnarian, working with Dr. Laneman, completed his Master's thesis on energy-efficient scheduling in OFDMA-based networks. The work focused on understating the effect of higher communication layers on the efficiency of radio resource consumption. Different algorithms for radio resource management were developed and tradeoffs among energy efficiency, queue stability and latency of wireless networks with many users were studied.

7) Graduate student Tua Tamba, working with Dr. Lemmon completed his Ph.D. Disssertation on "Forecasting Regime Shifts in Nonlinear Dynamical Processes". This work used certificate methods to estimate the "resilience" of nonlinear processes to regime shifts caused by external disturbances. Regime shifts occur when the networked system's operating point shifts abruptly due to 1) the system state leaving the nominal equilibrium's region of attraction or 2) the disappearance or change in the nominal equlibrium's stability type (i.e. a local bifurcation). In both cases, certificates were found that allowed one to bound the mean first passage time of the system to a regime shift and the minimum distance-to-bifurcation. Initially the work was used to measure regime shift sensitivity in networked systems found in systems biology and ecology. The underlying models, however, are quite general and these methods can be applied to any networked dynamical

system which satisfy some underlying mass/energy conservation relation. Future work in the no-cost extension year will focus on applying these concepts to predict cascading congestion collapse in the ad hoc communication networks used in this project's multi-vehicle applications as well as developing methods to prevent sensitivity to such collapses.

8) Graduate student Zhao Wang working with Dr. Lemmon published two papers regarding the resilience of electrical power systems in the 2015 IEEE Power and Energy Society (PES) general meeting. Both of these papers deal with the resilience of "last mile" stressed power distribution networks. The paper, "A static voltage stability detector using only local measurements of droop-controlled generators for stressed power distribution networks", developed a local stability index using local measurments for generators in a stressed power network. The stability index is a real-time index measuring how "close" the power network is to a voltage collapse. The second paper, "Stability analysis of weak rural electrification microgrids with droop-controlled rotational and electronic distributed generators", provides sufficient conditions for voltage stability of weak microgrids consisting of both rotational and fast electronic generators. These conditions are in terms of network parameters characterizing the losses in transmission lines.

Specific Objectives:

Significant Results:

1) Dr. Lin and his student (J. Dai) developed a novel learning-based approach to the fault-tolerant control of multi-agent systems. This led to a published conference paper (J. Dai and H. Lin, “Learning-based design of fault-tolerant cooperative multi-agent systems,” in Proc. of the 2015 American Control Conference, Chicago, IL, July 1-3, 2015.)

2) Dr. Lin and his former student (A. Karimoddini) proposed approach develops a unified hierarchical hybrid control framework using a bismulation-based abstraction technique over the partitioned motion space that can be applied to autonomous aerial robots (3-D symbolic motion planning) or ground vehicles (2-D symbolic motion planning). This work led to a journal publication (A. Karimoddini and H. Lin, “Hierarchical hybrid symbolic robot motion planning and control,” Asian Journal of Control, vol. 17, no. 1, pp. 23-33, 2015.)

3). Dr. Lin and his former post-doc (Z. Ji) investigated the controllability of multi-agent systems and found that the controllability of a multi-agent system is solely decided by its communication topology structure. Based on this finding, principles to construct uncontrollable communication topologies were identified. This study leads to a journal publication (Z. Ji, H. Lin, and H. Yu, “Protocols design and uncontrollable topologies construction for multiagent networks,” IEEE Transactions on Automatic Control, vol. 60, no. 3, pp. 781-786, 2015.)

4) Dr. Lin and his former student (T. Li) studied the multi-agent optimization problem and proposed a new geometric based cooperative optimization approach to deal with inseparable cost functions. This work led to an accepted journal paper (T. Li, H. Lin, and J. Zhao, “Cooperative optimization with inseparable cost functions,” to appear in IET Control Theory & Applications, 2015.)

5) Graduate student Sahand Golnarian, working with Dr. Laneman, developed a model and optimization algorithms for downlink scheduling of a transmissions in the context of orthogonal frequency division multiplex (OFDM) physical layer. These algorithms allow for a tradeoff between latency and energy efficiency by adjusting the relative priorities of shorter queues vs. lower power consumption. The results were summarized in a M.S. thesis (S. Golnarian, “Energy-Efficient and Queue-Aware Resource Allocation in Uplink OFDM Systems for Wireless

M2M Communication," Master's thesis, University of Notre Dame, Notre Dame, IN, Dec. 2014.).

6) Graduate student Bin Hu, working with Dr. Lemmon published a journal paper in the Transactions on Automatic Control entitled "Distributed Switching Control to Achieve Almost Sure Safety for Leader-Follower Vehicular Networked Systems" that is schedule to appear in December 2015. This work shows how to reconfigure controllers used in leader-follower vehicular networks to ensure resilience to long term fading in the vehicular network's wireless communication links. A major result of the paper allows one to assure a stronger "safety" concept that asymptotically assures the almost-sure safety of the vehicular network.

7) Dr. Lemmon and graduate student Tua Tamba developed a computationally scalable way to bound the distance to bifurcation (D2B) in polynomial networked systems. The method takes advantage of the fact that "equilibrium fluxes" within these polynomial systems lie in a convex polyhedral cone of the parameter space. While the Jacobian matrix of the polynomial system is a bilinear function of the fluxes and state equilibria, it can be reparameterized using the concept of "elementary flux modes" found in systems biology to obtain a linear parameterization. In this case, therefore, the problem of determining the distance to bifurcation reduces to evaluating the robust stability of an affine parameter dependent system that can be easily solved using linear matrix inequalities (LMIs) rather than the more general semi-definite programming (SDP) methods we have used in the past. These results were summarized in a Ph.D. dissertation (T. Tamba, "Forecasting Regime Shifts in Nonlinear Dynamical Processes") as well as an accepted conference paper (M.Lemmon and T. Tamba, "Using Elementary Flux Modes to Estimate the Distance to Regime Shifts in Kinetic Systems") to be presented in the 5th IFAC workshop on the Analysis and Design of Hybrid Systems (ADHS 2015).

Key outcomes or
Other achievements:

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

This project provided opportunities for 6 undergraduate students (Joe Driano, Andrew Lasher, Jack Riely, Emanuelle Rezende, Joel Filho, and Linda Gong) to work on projects related to the DISCOVER lab and the development of the multi-robot/UAV coordination.

This project provided internship opportunities for 1 high school student (Delun Shi).

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, and also provide summer robotics engagement opportunities for South Bend Community Schools.

*** 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?**

1) The efforts of Dr. Laneman and his students will be focused on porting the M2M testbed to the new NI-based SDR platform. This team will work closely with Drs. Lin and Lemmon and their students to create a test network consisting of over-the-air transmissions among multiple, simulated robots running a distributed control and coordination algorithm. The simulated robots will generate realistic trafffic for the wireless network nodes to convey, allowing the

team to study sensitivity of the system performance to various wireless features and parameters. Between the simulated robots and lower-level aspects of the wireless stack, we will continue to evolve a "network middleware" interface through design, implementation, and experiments.

2) The recent work of Dr. Lemmon regarding the resilience of networked systems to regime shifts will be applied to the ad hoc wireless communication networks being to 1) predict the likelihood of cascading congestion occurring in ad hoc wireless communication networks and 2) to develop strategies for reducing network sensitivity to such congestion cascades. Network models will be based on the SDR-based platform and robotic application being used by Drs Laneman and Lin (see above). This work complements the earlier work of Dr. Lemmon and graduate student Bin Hu that focused on improving vehicular network system resilience to fading wireless links, by focusing instead on the resilience of communication network connectivity to such fading links.

Products

Books

Book Chapters

Conference Papers and Presentations

Zhao Wang and M.D. Lemmon (2015). *A static voltage stability detector using only local measurements of droop-controlled generators for stressed power distribution networks*. IEEE Power and Energy Society General Meeting. Denver Colorado. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

J. Dai and H. Lin (2014). *Automatic synthesis of cooperative multi-agent systems*. The 53rd IEEE Conference on Decision and Control. Los Angeles, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

B. Wu and H. Lin (2015). *Counterexample-guided permissive supervisor synthesis for probabilistic systems through learning*. 2015 American Control Conference. Chicago. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

B. Wu, H. Lin, and M. Lemmon (2014). *Formal methods for stability analysis of networked control systems with IEEE 802.15.4 protocol*. The 53rd IEEE Conference on Decision and Control. Los Angeles, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

X. Zhang, B. Wu and H. Lin (2015). *Learning Based Supervisor Synthesis of POMDP for PCTL Specifications*. The 54th IEEE Conference on Decision and Control. Osaka, Japan. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

J. Dai and H. Lin (2015). *Learning-based design of fault-tolerant cooperative multi-agent systems*. 2015 American Control Conference. Chicago. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Zhao Wang and M.D. Lemmon (2015). *Stability analysis of weak rural electrification microgrids with droop-controlled rotational and electronic distributed generators*. IEEE Power and Energy Society General Meeting. Denver Colorado. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Xiaobin Zhang and Hai Lin (2015). *Stochastic hybrid systems modeling and performance verication of behavior-based robots*. 2015 American Control Conference. Chicago. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M.D. Lemmon and T. Tamba (2015). *Using Elementary Flux Modes to Estimate the Distance to Regime Shifts in Kinetic Systems*. IFAC Conference on the Analysis and Design of Hybrid Systems (ADHS 2015). Atlanta, Georgia. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Journals

A. Karimoddini and H. Lin (2015). Hierarchical hybrid symbolic robot motion planning and control. *Asian Journal of Control*. 17 (1), 23. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

A. Karimoddini, H. Lin, B. M. Chen, and T. H. Lee (2014). Hierarchical hybrid modelling and control of an unmanned helicopter. *International Journal of Control*. 87 (9), 1779. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Bin Hu and M.D. Lemmon (2015). Distributed Switching Control to Achieve Almost Sure Safety for Leader-Follower Vehicular Networked Systems. *IEEE Transactions on Automatic Control*. PP (99), . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: DOI: 10.1109/TAC.2015.2418451

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

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*. 12 (3), 218. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

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

Q. Quan, K.Y. Cai, and H. Lin (2015). Additive-state-decomposition-based tracking control framework for a class of nonminimum phase systems with measurable nonlinearities and unknown disturbances. *International Journal of Robust and Nonlinear Control*. 25 (2), 163. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

T. Li, H. Lin, and J. Zhao (2015). Cooperative optimization with inseparable cost functions. *IET Control Theory & Applications*. . Status = ACCEPTED; 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

Z. Ji, H. Lin, and H. Yu (2015). Protocols design and uncontrollable topologies construction for multiagent networks. *IEEE Transactions on Automatic Control*. 60 (3), 781. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Ebrahim MolavianJazi. *A Unified Approach to Gaussian Channels with Finite Blocklength*. (2014). University of Notre Dame. Acknowledgement of Federal Support = No

Sahand Golnarian. *Energy-Efficient and Queue-Aware Resource Allocation in Uplink OFDM Systems for Wireless M2M Communication*. (2014). University of Notre Dame. Acknowledgement of Federal Support = No

Tua A. Tamba. *Forecasting Regime Shifts in Nonlinear Dynamical Processes*. (2015). University of Notre Dame. Acknowledgement of Federal Support = No

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 Website for NSF Grant CNS-1239222

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
Cai, Mingming	Graduate Student (research assistant)	7
Dai, Jin	Graduate Student (research assistant)	12
Golnarian, Sahand	Graduate Student (research assistant)	9
Hu, Bin	Graduate Student (research assistant)	3
Partovi, Alireza	Graduate Student (research assistant)	0
Tamba, Tua	Graduate Student (research assistant)	6
Wang, Zhao	Graduate Student (research assistant)	3
Wu, Bo	Graduate Student (research assistant)	12
Zhang, Xiaobin	Graduate Student (research assistant)	0

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 responsible for managing overall project.

Funding Support: N/A

International Collaboration: No
International Travel: No

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

Contribution to the Project: Dr. Laneman coordinated the efforts of graduate students Sahand Golnarian and Mingming Cai to develop the SDR-based M2M testbed. He also supervised Sahand Golnarian's M.S. thesis.

Funding Support: N/A

International Collaboration: No
International Travel: No

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 Ph.D. students - directs development of project's robotic testbed - research area concerns learning of discrete-event systems and parallel task decomposition

Funding Support: 1 month summer salary

International Collaboration: No
International Travel: No

Mingming Cai
Email: mcai@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 7

Contribution to the Project: Graduate student working on the SDR platform for the M2M testbed.

Funding Support: N/A

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: 9

Contribution to the Project: Graduate student working on reliable and energy-efficient machine-to-machine communication, and our Gumstix and SDR testbeds. Sahand was away an an industry internship for 5/15/2015-8/15/2015.

Funding Support: N/A

International Collaboration: No
International Travel: No

Bin Hu
Email: bhu2@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

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

Alireza Partovi
Email: apartovi@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

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

Funding Support: Other funds from co-PI Dr. Lin.

International Collaboration: No
International Travel: No

Tua Tamba
Email: ttamba@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

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

Funding Support: NSF - Fulbright Fellow

International Collaboration: No
International Travel: No

Zhao Wang
Email: zwang6@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: investigating resilience of power distribution networks using wireless networks

Funding Support: NSF - Mitsubishi internship

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: Formal design of multi-robot cooperative tasking

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: 0

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.

What other collaborators or contacts have been involved?
Nothing to report

Impacts

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

The findings from this project provide a formal analytical basis for improving the resilience of wireless sensor-actuator networks (WSAN) to fading in communication links and system faults.

What is the impact on other disciplines?

The results to date are likely to impact our understanding of resilience with regard to ecological systems, systems biology, and electrical power networks.

What is the impact on the development of human resources?

a. 2 undergraduate students did research in Discover lab during Spring of 2015

Joe Driano, Andrew Lasher

b. 4 undergraduate students did summer research in Discover lab during Summer of 2015

Jack Riely, Emanuelle Rezende, Joel Filho, and Linda Gong

c. 1 high-school kid, Delun Shi, did summer intern in Discover lab, summer 2015

d. 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.

e. Provided summer robotics engagement opportunities for South Bend Community Schools (around 60 k-12 kids and over then teachers attended).

f. 1 PhD student graduated (T. Tamba) who will be returning to Indonesia as a post-doctoral assistant.

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?
Nothing to report.

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

Changes/Problems

Changes in approach and reason for change

The original project concept was to make use of WiFi dongles to implement the Machine-to-Machine (M2M) communication infrastructure. Due to the propriety nature of the dongle interfaces, we had to switch to those software-defined radio (SDR) platorms supported by National Instruments (NI). These platforms are significantly more bulky than WiFi dongles which means that they could only be used on our ground robot testbeds (rather than the aerial drones). Under Dr. Laneman's direction, these SDR platforms are now working and the revised workplan is to integrate them into a multi-robot simulation (MobileSim) as a first step for integrating into the hardware testbed developed by Dr. Lin.

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

No anticipated problems with the revised workplan.

Changes that have a significant impact on expenditures

No significant impact on expenditures.

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.