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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:	10/01/2015 - 09/30/2016
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 students, Xiaobin Zhang and Bo Wu, working with Dr. Lin, investigated the supervisor synthesis problem for Partially Observable Markov Decision Process (POMDP) with respect to PCTL specifications. We used formal methods to learn a Deterministic Finite Automaton (DFA) as a supervisor that regulates the behavior of a Partially Observable Markov Decision Process (POMDP) so it satisfies a given specification in the Probabilistic Computation Tree Logic (PCTL). This was done mby modifying the L* learning algorithm and defining oracles for membership queries and conjectures. We further showed that the termination and correctness of the design algorithm are guaranteed.

2) Graduate student Bo Wu, working together with Dr. Lin, focused on the planning and decision making of multi-agent systems (MAS) under uncertainties. To capture the uncertainties, probabilistic models are adopted. To deal with the scalability issues, compositional and modular design approaches are used. The main novelty of the proposed method comes from the integration of methods from supervisory control, machine learning and formal verification. In particular, an automatic local supervisor synthesis framework based on learning and compositional model checking was adopted. This approach avoids the state-space explosion problem encountered in assume-guarantee reasoning by using a procedure that identifies faulty subsystems whenthe specification is not met. The termination and correctness of proposed design methods are formally proved.

3) Graduate Student Dai Jin, working with Dr. Lin, studied a formal design method for fault-tolerant multi-agent systems that integrates 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 the occurrence of a fault. Should a failure occur, the corresponding local supervisors is redesigned and the team is reconfigured. 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.

4) Graduate students Rafael DaSilva and Bo Wu, working with Dr. Lin, proposed an integrated task and motion planning (ITMP) for mobile robots in a dynamic environment with moving obstacles. The basic idea is to synthesize a global motion plan through composing simple local moves and actions, and to achieve its performance guarantee through modular and incremental verifications. The design consists of two steps. First, basic motion primitives are designed and verified locally. Then, a global motion path is built upon these certified motion primitives by concatenating them together. They model the motion primitives as hybrid automata and verify their safety through a Differential Dynamic Logic (dL). These proven safe motion primitives are then composed based on an encoding to Satisfiability Modulo Theories (SMT). The work generates correct plans for given task specifications that are formally proven safe even for moving obstacles.

5) Former graduate students M. Karimadini and A. Karimoddini, working with Dr. Lin, studied the task decomposition problem for cooperative multi-agent systems, and proposed necessary and sufficient conditions for task decomposability with respect to an arbitrary finite number of agents. It is furthermore shown that fulfilling the decomposed local tasks by individual agents guarantees the satisfaction of the original global decomposable task. A divide-and-conquer approach for cooperative tasking among multi-agent systems is proposed. The basic idea is to decompose an assigned global specification (given as a deterministic automaton) into subtasks for individual concurrent agents such that the fulfillment of these subtasks by each individual agent leads to the satisfaction of the global specification as a team. This work provides insights into what kinds of tasks can be achieved distributively, which helps designers specify achievable global tasks for a group of agents and design necessary information sharing among each other for a particular task.

6) Graduate student Bin Hu working with Dr. Lemmon completed the study of an approach to the resilient control of automated vehicular networks over wireless communication networks. The work shows how to design switched controllers whose switching is triggered by sensed changes in the channel state. The controllers assure amost-sure stochastic safety (almost-sure safety) under outages that can be modeled as Markov chains. The proposed approach was successfully demonstrated on a multiple leader-follower chain. This work is significant because it provides a much stronger notion of probabilistic safety than has been traditionally used. The work demonstrates that switched controller strategies can indeed be used to provide strong probabilistic guarantees for safety-critical systems using wireless communication networks.

7) Graduate student Sahand Golnarian working with Dr. Laneman and Dr. Lemmon completed his study of the outage performance of 802.11 broadcasting in vehicular networks. The analysis provides analytical expressions characterizing the probability distribution of message latency and loss as a function of various control parameters within the 802.11 medium access control (MAC) protocol. This work is significant because it exposes the relationship between outage performance and MAC control parameters, thereby providing another mechanism for adaptation to enhance the resiliency of the application.

8) Graduate student Sahand Golnarian, Mingming Cai, Rafael DaSilva, and Yinhao Zhu working with Drs. Laneman, Lin, and Lemmon completed the development of a Hardware-in-the-Loop autonomous vehicular network simulator (Hil-AVN). This system uses software to simulate vehicular systems while realizing inter-vehicle communication using hardware radios. Each vehicle is simulated in MobileSim on a laptap that connects over Ethernet to a National Instruments (NI) computer that is connected to up to 6 software defined radios (SDR). The SDR's are configured to support existing WiFi bands found in autonomous vehicular networks. Each simulated vehicle, therefore, has a dedicated hardware radio. This setup allows one to adaptively control up to 6 simulated vehicles by reconfiguration of the vehicular controls and the hardware radio's MAC protocol. The simulation facility is significant for it provides a way to evaluate coordinated control of vehicles and radios in an environment consistent with what one will find in real-life AVNs.

Specific Objectives:

1) Development of a hybrid hierarchical control architecture that integrates supervisory control, verification and regular inference to achieve automated top-down design of resilient multi-agent systems. This objective was partially realized with the publication of R. DaSilva's (Dr. Lin's) conference paper "Formal Design of Robot Integrated Task and Motion Planning.", CDC 2016

2) Development of a switched control architecture that ensures almost-sure safety in vehicular networked systems using RF wireless communication. This objective was met with the publication of B. Hu (Dr. Lemmon) journal paper, "Distributed Switching Control

to Achieve Almost Sure Safety for Leader-Follower Vehicular Networked Systems" (IEEE-TAC 2015) and the successful defense of B. Hu's doctoral dissertation "Stochastic Safety and Efficiency for Vehicular Networked Systems: Theories and Applications", (Notre Dame 2016).

3) Analyzing the way in which an 802.11 MAC protocol's control parameters (backoff length) impact the radio channel's outage performance. This objective was realized with the publication of S. Golnarian (Dr. Laneman and Lemmon) conference paper, "On the outage performance of an IEEE 802.11 Broadcast Scheme in Vehicular Ad Hoc Networks" (Allerton 2016) and the successful defense of S. Golnarian's MS thesis, "Energy-Efficeint and Queue-Aware Resource Allocationin Uplink OFDM Systems for Wireless M2M Communication" (Notre Dame 2014).

4) Development of a mathematical framework for quantitatively evaluating the resilience in a wide range of networked systems found in science and engineering. This objective was realized with Tua Tamba's (Dr. Lemmon) successful defense of his doctoral dissertation "Forecasting Regime Shifts in Nonlinear Dynamical Processes", (Notre Dame 2015) and Z. Wang's (Dr. Lemmon) successful defense of his doctoral dissertation "Using Utility Scale Microgrids in Deregulated Wholesale Power Markets", (2016).

5) Development of a testbed that integrates M2M radios with controllable vehicles. This objective was realized with the development of Dr. Laneman's hardware in the loop (HiL) autonomous vehicular network (AVN) testbed that was described in "Major Accomplishments" (2016) and the establishment of Dr. Lin's DISCOVER multi-robot testbed in the project's first year.

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 in 2016 American Control Conference, titled “Achieving fault-tolerance and safety of discrete-event systems through learning.”

2) Dr. Lin and his student (Bo Wu) proposed an automatic local supervisor synthesis framework for a network of probablistic systems based on learning and compositional model checking. This led to a published conference paper in 2016 American Control Conference, titled "Counterexample-guided Distributed Permissive Supervisor Synthesis for Probabilistic Multi-agent Systems through Learning."

3) Dr. Lin and his students (Rafael Rodrigues da Silva, Bo Wu) investigated an integrated task and motion planning problem for mobile robots in dynamic and partially known environments based on formal methods. This led to an accepted paper to appear in the 2016 Conference on Decision and Control, entitled "Formal Design of Robot Integrated Task and Motion Planning."

4) Dr. Lin and his former students (M. Karimadini and A. Karimoddini) studied the task decomposition problem for cooperative multi-agent systems, and proposed necessary and sufficient conditions for task decomposability with respect to an arbitrary finite number of agents. This led to a journal publication entitled "Cooperative Tasking for Deterministic Specification Automata."

5) 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.)

6) Dr. Lemmon and his student (Bin Hu) studied almost sure notions of safety in vehicular networks communicating over RF wireless channels. This work led to two accepted journal papers (B. Hu and M.D. Lemmon, "Distributed Switching Control to

Achieve Almost Sure Safety for Leader-Follower Vehicular Networked Systems", IEEE Transactions on Automatic Control, Vol 60:12(3195-3209), 2015.) and (L. Li, X. Wang, and M.D. Lemmon, "Efficiently Attentive Event-Triggered Control Systems with Limited Bandwidth", IEEE Transactions on Automatic Control, PP(99):1-1, DOI 10.1109/TAC.2016.257381, 2016).

7) Dr Laneman, Dr. Lemmon, and their student (Sahand Golnarian) studied the outage performance of 802.11 MAC protocols. This work led to a conference paper (S. Golnarian, J.N. Laneman, and M.D. Lemmon, "On the outage performance of an IEEE 802.11 Broadcast Scheme in Vehicular Ad Hoc Networks", 54th Allerton Conference on Communication, Control, and Computing, 2016.)

8) Dr. Lemmon and his student (Z Wang) studied resilience of microgrids. This work led to two conference papers (Z. Wang and M.D. Lemmon, "Utility-scale microgrids and day-ahead markets: a new curtailment?", Power and Energy Society General Meeting (PESGM) 2016) and (Z. Wang and M.D. Lemmon, "Using decentralized secondary controllers to improve transient stability of generators in lossy power networks", American Control Conference, 2016).

Key outcomes or Other achievements:

1. A control theoretic top-down design framework for multi-robot cooperative tasking and associated hybrid hierarchical control architecture that integrates regular inference, supervisory control and computational verification methods. This outcome was described in the conference paper "Formal Design of Robot Integrated Task and Motion Planning.", CDC 2016

2. The establishment of two testbed/lab facilities. The first lab (DISCOVER) is an indoor multi-robot testbed (Dr. Lin) that includes autonomous unmanned ground (UGM) and aerial vehicles (UAVs). The second lab (HiL-AVN) is a hardware-in-the-loop autonomous vehicular network simulator (Dr. Laneman) in which simulated vehicle's communicate over a network of software defined radios.

3. The development of resilient control strategies for networked systems communicating over RF wireless links (Dr. Lemmon). This work focused on assuring safe operation when the RF link has unexpected outages. Resiliency in such a scenario means 1) that the system can reduce the likelihood of outages and 2) the system can reconfigure itself to recover safe operation once an outage has occurred. The first objective of reducing vulnerability to outages was addressed by linking radio control parameters in the MAC layer to actual outage performance. This was done for IEEE 802.15 MAC (B.Wu, H. Lin, and M.D. Lemmon, ``Stability analysis for wireless networked control systems in unsolotted IEEE 802.15.4 protocol, ICCA, 2014) and 802.11 MAC protocols (S.Golnarian, J.N. Laneman, and M.D. Lemmon, "On the outage performance of an IEEE 802.11 broadcast scheme in vehicular ad hoc networks", Allerton, 2016). The second objective of recovering from link outages was addressed using a switched vehicle control strategy that appeared as a journal publication (B. Hu and M.D. Lemmon, "Distributed Switching Control to Achieve Almost Sure Safety for Leader-Follower Vehicular Networked Systems", IEEE-TAC, 2015) and is comprehensively described in Bin Hu's Ph.D. dissertation "Stochastic Safety and Efficiency for Vehicular Networked Systems: Theories and Applications", (Notre Dame 2016). A related outcome that was originally started in work prior to this grant found ways of reducing how often a control application needed to use the wireless link. This was accomplished through an event-triggering scheme whose usage of the link monotonically decreases over time. This outcome also appeared as a journal paper (L. Li, X. Wang, and M.D. Lemmon, "Efficiently Attentive Event-Triggered Control Systems with Limited Bandwidth", IEEE-TAC, to appear 2017).

4) The development of a mathematical framework (Dr. Lemmon) to quantitatively evaluate how resilient a networked system would be. This outcome was developed in the context of biological networked systems (T. Tamba) and power networks (Z. Wang). In this framework, a system's resilience is characterized by its ability to continuously

recover from catastrophic events. The initial collapse from its nominal configuration is triggered by the environment and is called a "regime shift". The recovery is also triggered by a regime shift, but in this case that shift is initiated by the user. Quantitative measures of resiliency, therefore, may be obtained by determining how large of a system perturbation would trigger a regime shift. This outcome showed how to use the existence of certificate functions to measure how close a system was to a regime shift and the framework is documented in T. Tamba's Ph.D. dissertation "Forecasting Regime Shifts in Nonlinear Dynamical Processes" (Notre Dame 2016). It was found that when the barrier certificates were chosen fom the space of sum-of-square (SoS) polynomials, that the computational complexity of the search prevented the use of this framework for extremely large systems. One major outcome of this effort was to find a way around this limitation by projecting the system in a way that brought out an affine structure to the certificates, thereby allowing one to recast the search for a certificate as a linear matrix inequality. This discovery was documented in the conference paper M. D. Lemmon and T.A. Tamba, "Using elementary flux modes to estimate the distance to bifurcation in kinetic systems", Analysis and Design of Hybrid Systems, Atlanta, 2015.

*** 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).

Dr. 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.

Research results have also been disseminated through posting of outcomes and reports on the project's webpage (http://www3.nd.edu/~lemmon/projects/NSF-12-520/).

Research results have been disseminated through journal publications.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

A. Karimoddini and H. Lin (2015). Hierarchical hybrid symbolic robot motion planning and control. *Asian Journal of Control*. 17 (1), . 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*. 60 (12), 3195. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: DOI: 10.1109/TAC.2015.2418451

E. MolavianJazi and J.N. Laneman (2014). 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

H. Lin (2014). Mission Accomplished: An introduction to formal methods in mobile robot motion plan- ning and control. *Unmanned Systems*. 2 (2), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

H. Lin and P. J. Antsaklis (2014). Hybrid dynamical systems: An introduction to control and verifica- tion. *Foundations and Trends in Systems and Control*. 1 (1), 1. Status = PUBLISHED; 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), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Lichun Li, Xiaofeng Wang, and M.D. Lemmon (2016). Efficiently Attentive Event-Triggered Control Systems with Limited Information. *IEEE Transactions on Automatic Control*. PP (99), . Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1109/TAC.2016.2577381

M. Karimadini, A. Karimoddini, and H. Lin (2016). Cooperative Tasking For Deterministic Specification Automata. *Asian Journal of Control*. . Status = AWAITING_PUBLICATION; 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. Li and H. Lin (2016). Effects of Mixed-Modes on the Stability Analysis of Switched Time-Varying Delay Systems. *IEEE Transactions on Automatic Control*. . Status = AWAITING_PUBLICATION; 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 distur- bances. *International Journal of Robust and Nonlinear Control*. 25 (2), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Sahand Golnarian, J. Nicholas Laneman, and Michael D. Lemmon (2016). On the Outage Performance of an IEEE 802.11 Broadcast Scheme in Vehicular Ad Hoc Networks. *Proc. Allerton Conf. Communications, Control, and Computing*. . 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*. 9 (16), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

T.A. Tamba and M.D. Lemmon (2016). 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

Wang Zhao and M.D. Lemmon (2016). Utility-scale micro grids and day-ahead markets: a new curtailment?. *Power and Energy Society General Meeting (PESGM)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1109/PESGM.2016.7741749

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

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

Zhao Wang and M.D. Lemmon (2016). Using decentralized secondary controllers to improve transient stability of generators in lossy power networks. *American Control Conference*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1109/ACC.2016.7526595

Licenses

Other Conference Presentations / Papers

J. Dai, A. Karimoddini, and H. Lin (2016). *Achieving Fault-tolerance and Safety of Discrete-event Systems through Learning*. 2016 American Control Conference. Boston, MA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

B. Wu, J. Dai, and H. Lin (2015). *Combined Top-Down and Bottom-Up Approach to Cooperative Distributed Multi-Agent Control with Connectivity Constraints*. IFAC Con- ference on Analysis and Design of Hybrid Systems. Atlanta, Georgia. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

B. Wu and H. Lin (2016). *Counterexample-guided Distributed Permissive Supervisor Synthesis for Probabilistic Multi-agent Systems through Learning*. 2016 American Control Conference. Boston, MA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

X. Zhang, B. Wu, and H. Lin (2015). *Counterexample-guided permissive supervisor synthesis for proba- bilistic systems through learning*. 54th IEEE Conference on Decision and Control. Osaka, Japan. 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, IL. 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 = PUBLISHED; 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, IL. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

X. Zhang, Y. Zhu, and H. Lin (2016). *Performance Guaranteed Human-Robot Collaboration through Formal Design*. 2016 American Control Conference. Boston, MA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

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

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 Tamba. *Forecasting Regime Shifts in Nonlinear Dynamical Processes*. (2015). University of Notre Dame. Acknowledgement of Federal Support = Yes

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

Bin Hu. *Stochastic Safety and Efficiency for Vehicular Networked Systems: Theories and Applications*. (2016). University of Notre Dame. Acknowledgement of Federal Support = Yes

Zhao Wang. *Using Utility-scale Microgrids in Deregulated Wholesale Power Markets*. (2016). University of Notre Dame. Acknowledgement of Federal Support = Yes

Websites

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)	3
da Silva, Rafael	Graduate Student (research assistant)	3
Dai, Jin	Graduate Student (research assistant)	12
Golnarian, Sahand	Graduate Student (research assistant)	12
Hu, Bin	Graduate Student (research assistant)	6
Tamba, Tua	Graduate Student (research assistant)	12
Wang, Zhao	Graduate Student (research assistant)	12
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 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: Supervised graduate students working on vehicular network testbed and developing outage framework for performance characterization of wireless control networks with periodic broadcast mechanisms.

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: In charge of the development of formal methods in resilient multi-agent system theory and supervising students in the multi-robot testbed developments and experiments.

Funding Support: one month summer

International Collaboration: No
International Travel: No

Mingming Cai
Email: mcai@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

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

Rafael da Silva
Email: rrodri17@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Development of UGV testbed and carry out experiments.

Funding Support: Brazil scholarship CAPES/BR, BEX 13242/13-0

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 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: 6

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

Tua Tamba
Email: ttamba@nd.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

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: 12

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: 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.

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?

One outcome of this project was a mathematical framework for resilient systems that could be used in other scientific disciplines such as ecology.

What is the impact on the development of human resources?

a. 2 undergraduate students (Joe Driano, Andrew Lasher) did research in Discover lab during Spring of 2015

b. 4 undergraduate students (Jack Riely, Emanuelle Rezende, Joel Filho, and Linda Gong) did summer research in Discover lab during Summer of 2015

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).

What is the impact on physical resources that form infrastructure?

This project helps to develop 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.

This project helped develop the software defined radio (SDR) lab at the University of Notre Dame's Wireless Institute. The project established a Hardware-in-the-loop autonomous vehicle simulator in which the vehicles are simulated and communication over SDRs. The testbed serves to stimulate greater collaboration between Notre Dame researchers in multi-agent robotics and wireless communication.

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
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.