



AFRL-AFOSR-VA-TR-2016-0314

Distributed learning, extremum seeking, and model-free optimization for the resilient coordination of multi-agent adversarial groups

Sonia Martinez Diaz
UNIVERSITY OF CALIFORNIA SAN DIEGO
9500 GILMAN DR DEPT 621, OFFICE OF CONTRACT & GRANT ADMIN. 09
LA JOLLA, CA 92093-0621

09/07/2016
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTA2

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.					
1. REPORT DATE (DD-MM-YYYY) 30-08-2016		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) Jul-2012 - Jun-2016	
4. TITLE AND SUBTITLE Distributed learning, extremum seeking, and model-free optimization for the resilient coordination of multi-agent adversarial groups				5a. CONTRACT NUMBER FA9550-12-1-0183	
				5b. GRANT NUMBER AFOSR-11RSL548	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Sonia Martinez and Miroslav Krstic				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dept. of Mechanical and Aerospace Engineering, UC San Diego, 9500 Gilman Dr, La Jolla, CA 92093				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 North Randolph Street Suite 325, Room 3112 Arlington VA, 22203				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR/RTA-2/DyControls	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION A: Distribution approved for public release.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This proposal focuses on the analysis and design of coordination algorithms for multiple agents deployed in adversarial environments. The multi-agent systems can represent miscellaneous autonomous and semi-autonomous vehicles that are remotely controlled by operators. These groups can be subject to attacks from other external agents leading to complex networked adversarial settings. The proposal presents work in two main areas: 1) the use of a class of receding-horizon type of algorithms to overcome the effect of a type of uncoordinated attackers on a multi-vehicle-operator group, and 2) the use of extremum seeking (ES) techniques to learn Nash equilibria in finitely- and infinitely-many player noncooperative games and to solve high-dimensional optimization problems. Extensions and applications of these techniques were developed during the realization of the project.					
15. SUBJECT TERMS Dynamics and Controls					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Sonia Martinez
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 858-822-4243

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report on AFOSR grant FA09550-12-1-0183

Abstract:

This research effort belongs to the general area of distributed learning, and the control and coordination of multiple and single agent systems, and is led by Dr. Martinez and Dr. Krstic at UC San Diego. The work has particular impact on the development of a theory of autonomy science, which accounts for both the aspects of resilience under adversaries, and learning via extremum seeking, and distributed optimization techniques. During this period, several theoretical advancements as well as applications have been carried out, which are summarized as follows.

Research Results:

Dr. Martinez's effort focuses on the analysis and design of robust (multi-)agent coordination algorithms subject to failure and adversarial action. The agents can represent miscellaneous autonomous and semi-autonomous vehicles that are remotely controlled by operators. These groups can be subject to attacks from other external agents leading to complex networked adversarial settings. Attacks and malicious actions considered include Denial-of-Service (DoS), replay, and man in the middle attacks, eavesdropping and privacy violation, and, more recently, virus spreading. In addition to this, work to advance the state of the art in multi-agent systems has been continued.

Technical Results:

1. *A set of novel algorithms based on receding-horizon control and distributed parameter learning for the robust coordination of multi-agent systems.* A study of the tradeoffs in costs/effort of the algorithms under the following set of assumptions have been considered: (a) unknown adversaries introducing on/off disturbances to the system (e.g. denial of service), (b) partially known adversary, which modifies the control commands to a certain extent; however, the operator can exploit this model to learn the adversary, (c) the adversarial action aims to reconstruct the whole multi-agent system objective and control commands.
2. *Novel time-triggered, event-triggered, and receding-horizon-based control laws for remote system operation under DoS pulse-width modulated systems.* By means of parameter tuning that learns the characteristics of the DoS signal, event-triggering and time-triggering controls for a linear system are derived.
3. *Privacy preserving coordination algorithms for multi-agent systems.* Consensus algorithms that do not require agents to exchange state information, but secondary variables which do not allow for the reconstruction of the agents' states by an eavesdropping agent, are devised.
4. *Robust coordination (consensus) of multi-agent systems when these are subject to outlier measurements.* This is based on dynamic consensus algorithms combined

with RANSAC, which is a ‘voting strategy’ widely used in computer vision and that allows to deal with more than 50% outliers.

5. *Coordination (consensus and distributed optimization) of multi-agent systems using event-triggered control.* We studied problems of dynamic average consensus and a class of unconstrained continuous-time optimization algorithms for the coordination of multiple agents.
6. *Virus spreading mitigation distributed optimization algorithms over computer/robotic networks.* We have produced a variety of discrete-time and distributed optimization algorithms that can be used by a multi-operator group to decide on an optimal resource allocation subject to constraints and eradicate a virus spreading over a network. These algorithms have various robust features (such as robustness to initialization.)

We mention the following work under review, on subjects that are more related to the general topics of distributed learning, and optimization, in GPS denied environments:

1. *Distributed and discrete-time convex optimization algorithms subject for unknown cost functions.* This work, which is to appear, is similar to simultaneous perturbation stochastic approximation (SPSA), but based on recent theory of stochastic hybrid systems, and building on the discrete-time optimization algorithms of (6.) above. Thus, it does not have the limitations of SPSA such as diminishing step sizes.
2. *Control of single agents in GPS denied environments with obstacles but via an adaptation of the SPSA techniques.* Similar techniques as above can be applied for a wheeled-robot to reach the maximum of a convex cost function using projections to handle obstacles.

We report 33 publications refereed publications resulting from the grant for the period of performance; see the file ‘publications-afosr.pdf’ for more information.

Over the period of this grant, Co-PI **Dr. Krstic** has achieved several advances in extremum seeking described as follows:

Applications:

1. Extremum seeking has been established as one of the powerful methodologies for navigating autonomous vehicles in GPS-denied environments and several publications are reported below where advances in “source seeking” for single vehicles and groups of vehicles are presented. For example, an application to GPS-denied swarms of autonomous vehicles has been developed using stochastic extremum seeking, where the vehicles, starting from *distinct* and arbitrary positions, congregate to the source, while being fed a common (*indistinct*) control input.
2. Maximization of UAV endurance via using air turbulence with extremum seekings is also achieved in one of the publications below. Extremum seeking has

also been demonstrated on maximum power point tracking for photovoltaic arrays and for wind turbines.

3. ES has recently been implemented on the Mars Rover Curiosity and, as of May 2015, is used for the focusing of the ChemCam instrument which performs chemical testing of rocks at a distance by shining a laser beam, vaporizing, the rock surface, and focusing the reflection using a mirror back to a camera, with the help of extremum seeking, with the image subsequently being used in the chemical analysis of the rock.
4. Extremum seeking has also been implemented as the enabling technology in extreme ultraviolet light sources on ASML-Cymer silicon wafer scanners. This technology reduces the feature sizes of transistors on microchips by 4-10 times compared to previous technologies. Eight such units, at the price of \$100 million per unit, have been delivered to semiconductor fabs in Taiwan and China and running since 2014.
5. Extremum seeking has also been implemented on a kilometer-long accelerator at the Los Alamos National Laboratory for optimizing the high voltage converter modulator.

Theory: A number of theoretical advances in extremum seeking are reported in the publications listed below.

1. Extensions from deterministic to stochastic extremum seeking in several papers and one book.
2. Extension of ES from single-agent optimization to non-cooperative games in which the payoff functions are unknown to the players. ES performs the optimization of the players' strategies with a guaranteed convergence to the Nash equilibrium strategies.
3. Extension from gradient-like to Newton-like optimization strategies.
4. Development of ES algorithms for batch-to-batch optimization of open-loop finite-horizon optimal control strategies (which has been applied to lasers and in charged particle accelerators).
5. Development of model-free feedback algorithms for stabilization of nonlinear systems using the application of ES with candidate control Lyapunov functions.

Dr. Krstic reports about 50 peer-reviewed publications resulting from the grant for the period of performance. See the file 'publications-afors.pdf' for more information.

Next we give recognitions earned by Martinez and Krstic during this period.

AWARDS AND HONORS (Dr. Martinez)

CAREER PROMOTIONS AND RECOGNITIONS

2014	Full Professor, UC San Diego
2016	Senior Editor, IEEE Transactions on Control of Networked Systems

AWARDS TO STUDENTS

- 2011 *Minghui Zhu*, 2011 MAE Outstanding Graduate Student of the Year award, now an Assistant Professor at Penn State University
- 2013 *Solmaz S. Kia*, UC Presidential Fellowship recipient, now an Assistant Professor at UC Irvine
- 2015 *Andres Cortes*, 2015 MAE Outstanding Graduate Student of the Year award, now an Assistant Professor at Penn State University, now at EPRI

KEYNOTE LECTURES

- 2016 Keynote Speaker at the “*Workshop on Control and Observability of Network Dynamics*,” Mathematical Biosciences Institute, Ohio State University, April 2016
- 2016 Keynote Speaker at the “*1st So-Cal Robotics Symposium*,” Mathematical Biosciences Institute, Ohio State University, April 2016
- 2013 Keynote Speaker at the “*1st Workshop on Wireless Intelligent Sensor Networks (WiSeNet)*,” Duke University, 2013
- 2012 Plenary Speaker at the “*3rd IFAC Workshop on Distributed Estimation and Control of Networked Systems*” (NECSYS), Santa Barbara, 2012

AWARDS AND HONORS (Dr. Krstic)

CAREER RECOGNITIONS

- 2015 Foreign Member, *Academy of Engineering of Serbia*
- 2015 ASME DSCD *Nyquist Lecture Prize*
- 2015 Fellow of *SIAM* (Society for Industrial and Applied Mathematics)
- 2015 Associate Fellow of *AIAA* (American Institute for Aeronautics and Astronautics)
- 2014 Fellow of *ASME* (American Society of Mechanical Engineers)
- 2014 Fellow of *IET* (Institution of Engineering and Technology, UK)

OTHER MAJOR RECOGNITIONS

- 2016 *Qian Ren* Professor, Northeastern University, China
- 2015 Invitation Fellow, *Japan Society for the Promotion of Science*
- 2015 Honorary Professor, Dalian Maritime University, Donghua University, Chongqing University, Northeastern University, China
- 2013 Distinguished Visiting Fellow of the *Royal Academy of Engineering*, United Kingdom

BOOK PRIZE

- 2014 Harold Chestnut Textbook Prize, IFAC (International Federation for Automatic Control), triennial prize—the highest recognition for authoring a book in the field of control systems

AWARDS TO STUDENTS

- 2014 *Chancellor's Dissertation Medal* in Engineering (among 150 PhDs granted in 2013), UCSD, *Nikolaos Bekiaris-Liberis*
- 2014 *Best European Dissertation in Control* of Complex and Heterogeneous Systems, European Embedded Control Institute (EECI), *Delphine Bresch-Pietri*
- 2013 *Best University-wide Dissertation Award, Paris-Tech* (includes 12 most prestigious and oldest technical and business universities in the Paris region such as Ecole des

Mines, Ecole Polytechnique, ENSAE, etc.), *Delphine Bresch-Pietri*

KEYNOTE LECTURES

- 2015 *ASME Dynamic Systems and Control Conference, Nyquist Lecture*, Columbus, OH
- 2015 *IFAC Workshop on Adv. Control and Navigation for Autonomous Aerospace Vehicles*,
Sevilla, Spain
- 2014 *IEEE Conference on Decision and Control*, Los Angeles
- 2013 *Congreso Nacional de Control Automático*, Mexico
- 2013 *IFAC Workshop on Control of Systems Governed by Partial Diff. Equations*, Paris
- 2013 *IFAC Nonlinear Control Systems Symposium (NOLCOS)*, Toulouse, France
- 2013 *IFAC Workshop on Adaptation and Learning in Control and Signal Proc.*, Caen, France
- 2013 *IEEE Workshop on Open Problems and Challenges in Automotive Control*, Washington DC
- 2012 *IEEE Conference on Industrial Electronics and Applications*, Singapore
- 2012 *IEEE International Conference on Mechatronics and Automation*, Chengdu, China

FELICITATION LECTURES

- 2016 *Coron Fest*, UPMC, Sorbonne Universités, Paris
- 2015 *Praly Fest*, Ecole des Mines, Paris
- 2012 *Spong Fest*, University of Texas, Dallas
- 2012 *Sontag Fest*, Rutgers University
- 2012 *Bastin Fest*, Université Catholique de Louvain, Belgium

Publication List related to award FA09550-12-1-0183

Sonia Martínez

Books

- (JP1) M. Zhu and S. Martínez. *Distributed Optimization-Based Control of Multi-Agent Networks in Complex Environments*. Springer-Briefs in Electrical and Computer Engineering. 2015

Journal papers

- (JP-1) M. Zhu and S. Martínez. On distributed constrained formation control in operator-vehicle adversarial networks. *Automatica*, 49(12):3571–3582, 2013
- (JP-2) M. Zhu and S. Martínez. On the performance analysis of resilient networked control systems under replay attacks. *IEEE Transactions on Automatic Control*, 59(3):804–808, 2014
- (JP-3) M. Zhu and S. Martínez. On attack-resilient distributed formation control in operator-vehicle networks. *SIAM Journal on Control and Optimization*, 52(5):3176–3202, 2014
- (JP-4) S. S. Kia, J. Cortés, and S. Martínez. Dynamic average consensus under limited control authority and privacy requirements. *International Journal on Robust and Nonlinear Control*, 25(13):1941–1966, 2015
- (JP-5) E. Montijano, J.I. Montijano, C. Sagüés, and S. Martínez. Robust discrete-time dynamic average consensus. *Automatica*, 50(12):3131–3138, 2014
- (JP-6) E. Montijano, S. Martínez, and C. Sagüés. Distributed robust consensus using RANSAC and dynamic opinions. *IEEE Transactions on Control Systems Technology*, 23(1):150–163, 2015
- (JP-7) S. S. Kia, J. Cortés, and S. Martínez. Distributed convex optimization via continuous time coordination algorithms with discrete-time communication. *Automatica*, 55:254–264, 2015
- (JP-8) S. S. Kia, J. Cortés, and S. Martínez. Distributed event-triggered communication for dynamic average consensus in networked systems. *Automatica*, 59:112–119, 2015
- (JP-9) H. Shisheh Foroush and S. Martínez. On triggering control of single-input linear systems under pulse-width modulated DoS jamming attacks. *SIAM Journal on Control and Optimization*, 2016. Subject to minor revision
- (JP-10) E. Ramírez and S. Martínez. A distributed nonlinear dynamics for virus spread control. *Automatica*, 2016. To appear
- (JP-11) E. Ramírez and S. Martínez. Distributed and robust fair optimization applied to virus diffusion control. *IEEE Transactions on Network Science and Engineering*, 2016. Under review
- (JP-12) E. Ramírez and S. Martínez. Distributed discrete-time optimization algorithms with application to resource allocation in epidemics control. *Optimal Control Applications and Methods*, 2016. Under review

Conference proceedings

- (CP-1) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control and European Control Conference*, pages 6624–6629, Orlando, FL, USA, December 2011
- (CP-2) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control*, pages 6624–6629, Orlando, FL, USA, December 2011

- (CP-3) M. Zhu and S. Martínez. Stackelberg game analysis of correlated attacks in cyber-physical system. In *American Control Conference*, pages 4063–4068, June 2011
- (CP-4) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control and European Control Conference*, pages 6624–6629, Orlando, Florida, December 2011
- (CP-5) H. Shisheh Foroush and S. Martínez. On event-triggered control of linear systems under periodic Denial of Service attacks. In *IEEE Int. Conf. on Decision and Control*, pages 2551–2556, Maui, HI, USA, December 2012
- (CP-6) M. Zhu and S. Martínez. On distributed resilient consensus against replay attacks in adversarial networks. In *American Control Conference*, pages 3553–3558, Montreal, Canada, 2012
- (CP-7) H. Shisheh Foroush and S. Martínez. On multi-input controllable linear systems under unknown periodic DoS jamming attacks. In *SIAM Conference on Control and Its Applications (CT)*, pages 222–229, San Diego, CA, January 2013
- (CP-8) S.S. Kia, J. Cortés, and S. Martínez. Saturation-tolerant average consensus with controllable rates of convergence. In *SIAM Conference on Control and Its Applications (CT)*, pages 121–128, San Diego, CA, January 2013
- (CP-9) S. S. Kia, J. Cortés, and S. Martínez. Periodic and event-triggered communication for distributed continuous-time convex optimization. In *American Control Conference*, pages 5010–5015, Portland, OR, 2014
- (CP-10) S. S. Kia, J. Cortés, and S. Martínez. Dynamic average consensus with distributed event-triggered communication. In *IEEE Int. Conf. on Decision and Control*, pages 890–895, Los Angeles, CA, USA, December 2014
- (CP-11) E. Montijano, J. I. Montijano, C. Sagués, and S. Martínez. Step-size analysis in discrete-time dynamic average consensus. In *American Control Conference*, pages 5127–5132, Portland, OR, June 2014
- (CP-12) H. Shisheh Foroush and S. Martínez. On the robustness of event-based synchronization under switching interactions. In *IEEE Int. Conf. on Decision and Control*, pages 2001–2006, Los Angeles, CA, USA, December 2014
- (CP-13) E. Ramírez and S. Martínez. A distributed algorithm for virus spread minimization. In *American Control Conference*, pages 184–189, Portland, OR, USA, June 2014
- (CP-14) E. Ramírez and S. Martínez. Distributed and robust fair resource allocation applied to virus spread minimization. In *American Control Conference*, pages 1065–1070, Chicago, IL, USA, July 2015
- (CP-15) E. Ramírez and S. Martínez. Distributed stopping criteria for the power iteration applied to virus mitigation. In *Asilomar Conference on Signals, Systems, and Computers*, pages 1328–1332, Pacific Grove, CA, November 2015
- (CP-16) E. Ramírez and S. Martínez. Distributed and robust resource allocation algorithms for multi-agent systems via discrete-time iterations. In *IEEE Int. Conf. on Decision and Control*, pages 1390–1395, Osaka, Japan, December 2015
- (CP-17) E. Ramírez and S. Martínez. Gradient-free distributed resource allocation via simultaneous perturbation stochastic approximation. In *Allerton Conf. on Communications, Control and Computing*, Monticello, IL, USA, September 2016. To appear
- (CP-18) E. Ramírez and S. Martínez. Constrained source seeking for mobile robots via stochastic approximation. In *IEEE Int. Conf. on Decision and Control*, Las Vegas, NV, USA, December 2016. To appear

Invited book chapters

- (BC-1) M. Zhu and S. Martínez. *Cyber-security for industrial control systems: from the viewpoint of close-loop*, chapter 9: Distributed resilient control of operator-vehicle networks under cyber attacks. CRC Press, Taylor and Francis, 2016
- (BC-2) H. Shisheh Foroush and S. Martínez. *Principles of Cyber Physical Systems*, chapter On triggering control techniques for cyber-physical systems. Cambridge University Press, 2016

Publications by Co-PI Miroslav Krstic under the period of the grant

We report next about 50 peer-reviewed publications resulting from the grant for the period of performance.

Books

1. S.-J. Liu and M. Krstic, [*Stochastic Averaging and Stochastic Extremum Seeking*](#), Springer, 2012.
2. N. Bekiaris-Liberis, [*Nonlinear Control Under Nonconstant Delays*](#), SIAM, 2013.
3. I. Karafyllis and M. Krstic, *Predictor Feedback for Delay Systems: Implementations and Approximations*, Springer, 2016.

Journal Papers

1. N. Ghods and M. Krstic, "Multiagent deployment over a source," *IEEE Transactions on Control Systems Technology*, vol. 20, pp. 277-285, 2012.
2. P. Frihauf, M. Krstic, and T. Basar, "Nash equilibrium seeking in non-cooperative games," *IEEE Transactions on Automatic Control*, vol. 57, pp. 1192-1207, 2012.
3. B. Ren, P. Frihauf, R. Rafac, and M. Krstic, "Laser pulse shaping via extremum seeking," *Control Engineering Practice*, vol. 20, pp. 678-683, 2012.
4. A. Ghaffari, M. Krstic, and D. Nesic, "Multivariable Newton-based extremum seeking," *Automatica*, vol. 48, pp. 1759-1767, 2012.
5. J. Krieger and M. Krstic, "Aircraft endurance maximization at medium Mach numbers by extremum seeking," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 36, pp. 390-403, 2013.
6. A. Scheinker and M. Krstic, "Maximum-seeking for CLFs: Universal semiglobally stabilizing feedback under unknown control directions," *IEEE Transactions on Automatic Control*, vol. 58, pp. 1107-1122, 2013.
7. P. Frihauf, M. Krstic, and T. Basar, "Finite-horizon LQ control for unknown discrete-time linear systems via extremum seeking," *European Journal of Control*, vol. 19, pp. 399-407, 2013.
8. A. Scheinker, M. Bland, M. Krstic, and J. Audia, "Rise-time optimization of accelerator high voltage converter modulator by extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 34-43, 2014.
9. A. Scheinker and M. Krstic, "Non- C^2 Lie bracket averaging for non-smooth extremum seekers," *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 136, paper 011010, 2014.
10. A. Scheinker and M. Krstic, "Extremum seeking with bounded update rates," *Systems and Control Letters*, vol. 63, pp. 25-31, 2014.
11. A. Ghaffari, M. Krstic, and S. Seshagiri, "Extremum seeking for wind and solar energy applications," *Dynamic Systems and Control*, vol. 2, pp. 13-21, 2014.
12. S.-J. Liu and M. Krstic, "Newton-based stochastic extremum seeking," *Automatica*, vol. 50, pp. 952-961, 2014.

13. P. Frihauf, S.-J. Liu, and M. Krstic, "A single forward-velocity control signal for stochastic source seeking with multiple nonholonomic vehicles," *ASME Journal of Dynamic Systems, Measurement, and Control*, paper 051024, 2014.
14. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power optimization for photovoltaic micro-converters using multivariable Newton-based extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 2141-2149, 2014.
15. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power optimization and control in wind energy conversion systems using extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 1684-1695, 2014.
16. A. Ghaffari, S. Seshagiri, and M. Krstic, "Multivariable maximum power point tracking for photovoltaic micro-converters using extremum seeking," *Control Engineering Practice*, vol. 35, pp. 83-91, 2015.
17. H.-B. Durr, M. Krstic, A. Scheinker, and C. Ebenbauer, "Singularly perturbed Lie bracket approximation," *IEEE Transactions on Automatic Control*, vol. 60, 3287-3292, 2015.
18. S.-J. Liu and M. Krstic, "Stochastic averaging in discrete time and its applications to extremum seeking," *IEEE Transactions on Automatic Control*, vol. 61, pp. 190-102, 2016.
19. S. Z. Khong, D. Nesic, and M. Krstic, "A non-model based extremum seeking approach to iterative learning control," *Automatica*.
20. T. R. Oliveira, M. Krstic, and D. Tsubakino, "Extremum seeking for static maps with delays," *IEEE Transactions on Automatic Control*.
21. A. Raisch and M. Krstic, "Overshoot-free steering-based source seeking," *IEEE Transactions on Control Systems Technology*.

Refereed Conference Papers

1. Scheinker, M. Krstic, "A Universal Extremum Seeking-based Stabilizer for Unknown LTV Systems with Unknown Control Directions," *American Control Conference*, 2012.
2. Ghaffari, S. Seshagiri, M. Krstic, "Power Optimization for Photovoltaic Micro-Converters using Multivariable Gradient-Based Extremum-Seeking," *American Control Conference*, 2012.
3. A. Ghaffari, S. Seshagiri, M. Krstic, "High-fidelity photovoltaic array modeling for advanced MPPT design," *2012 IEEE Canadian Conference on Electrical and Computer Engineering*.
4. Ghaffari, S. Seshagiri, M. Krstic, "High-fidelity DC-DC converter modeling for advanced MPPT design," *2012 IEEE Canadian Conference on Electrical and Computer Engineering*.
5. S.-J. Liu, P. Frihauf, and M. Krstic, "Stochastic source seeking with tuning of forward velocity," *2012 Chinese Control Conference*.
6. P. Frihauf, S.-J. Liu, and M. Krstic, "Stochastic source seeking with multiple nonholonomic vehicles via a single forward-velocity control signal," *2012 ASME Dynamic Systems and Control Conference*.
7. A. Scheinker and M. Krstic, "Extremum Seeking-based Tracking for Unknown Systems with Unknown Control Directions," *Proceedings of the 2012 IEEE Conference on Decision and Control*.

8. S.-J. Liu and M. Krstic, "Newton-Based Stochastic Extremum Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
9. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power Optimization for Photovoltaic Micro-Converters using Multivariable Newton-Based Extremum-Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
10. P. Frihauf, M. Krstic, and T. Basar, "Finite-Horizon LQ Control for Unknown Discrete-Time Systems via Extremum Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
11. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power optimization and control in wind energy conversion systems using extremum seeking," *American Control Conference*, 2013.
12. S.-J. Liu and M. Krstic, "Stochastic averaging in discrete time," *Chinese Control Conference*, 2013.
13. G. Mills and M. Krstic, "Gradient based projection method for constrained optimization," *2013 IEEE Conference on Decision and Control*.
14. M. Krstic, A. Ghaffari, and S. Seshagiri, "Extremum seeking for wind and solar energy applications," *1st International Conference on Electrical, Electronic, and Computing Engineering*, Vrnjacka Banja, Serbia, 2014.
15. M. Krstic, A. Ghaffari, and S. Seshagiri, "Extremum seeking for wind and solar energy applications," *11th World Congress on Intelligent Control and Automation*, Shenyang, China, 2014.
16. S. Liu and M. Krstic, "Discrete-time stochastic extremum seeking," *IFAC World Congress*, 2014.
17. A. Ghaffari, S. Moura, and M. Krstic, "Analytical modeling and integral control of homogeneous thermostatically controlled load populations," *ASME Dynamic Systems and Control Conference*, 2014.
18. G. Mills and M. Krstic, "Constrained extremum seeking in 1 dimension," *IEEE Conference on Decision and Control*, 2014.
19. T. Roux Oliveira, M. Krstic, and D. Tsubakino, "Extremum seeking for time-delay systems - Part I: output delays," *American Control Conference*, 2015.
20. T. Roux Oliveira and M. Krstic, "Gradient extremum seeking with delays," *12th IFAC Workshop on Time Delay Systems*, 2015.
21. T. Roux Oliveira and M. Krstic, "Newton-based extremum seeking under actuator and sensor delays," *12th IFAC Workshop on Time Delay Systems*, 2015.
22. G. Mills and M. Krstic, "Maximizing Higher Derivatives of Unknown Maps with Extremum Seeking," *IEEE Conference on Decision and Control*, 2015.
23. T. R. Oliveira, M. Krstic, and D. Tsubakino, "Extremum Seeking subject to Multiple and Distinct Input Delays," *IEEE Conference on Decision and Control*, 2015.
24. G. Mills and M. Krstic, "Maximizing Higher Derivatives of Unknown Maps with Stochastic Extremum Seeking," *American Control Conference*, 2016.
25. S. Z. Khong, D. Nesic, M. Krstic, "An extremum seeking approach to sampled-data iterative learning control of continuous-time nonlinear systems," *10th IFAC Symposium on Nonlinear Control Systems*, Monterrey, CA, 2016.

AFOSR Deliverables Submission Survey

Response ID:6754 Data

1.

Report Type

Final Report

Primary Contact Email

Contact email if there is a problem with the report.

soniamd@ucsd.edu

Primary Contact Phone Number

Contact phone number if there is a problem with the report

8588224243

Organization / Institution name

UC San Diego

Grant/Contract Title

The full title of the funded effort.

Distributed learning, extremum seeking, and model-free optimization for the resilient coordination of multi-agent adversarial groups

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0183

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Sonia Martinez

Program Officer

The AFOSR Program Officer currently assigned to the award

Frederick Leve

Reporting Period Start Date

07/01/2012

Reporting Period End Date

06/30/2016

Abstract

This research effort belongs to the general area of distributed learning, and the control and coordination of multiple and single agent systems. The work has particular impact on the development of a theory of autonomy science, which accounts for both the aspects of resilience under adversaries, and learning via extremum seeking, and distributed optimization techniques. During this period, several theoretical advancements as well as applications on this front have been developed, which are summarized in full detail in the Report Document file.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

DISTRIBUTION A: Distribution approved for public release.

Please attach your [SF298](#) form. A blank SF298 can be found [here](#). Please do not password protect or secure the PDF. The maximum file size for an SF298 is 50MB.

[sf0298.pdf](#)

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF. The maximum file size for the Report Document is 50MB.

[final-report.pdf](#)

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

Please see them at the end of the final report file.

New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

None

Change in AFOSR Program Officer, if any:

The program officer changed from Fariba Fahroo to Frederik Leve

Extensions granted or milestones slipped, if any:

none

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Aug 30, 2016 18:18:52 Success: Email Sent to: soniamd@ucsd.edu