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6. AUTHORS
Frank L. Lewis

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5e. TASK NUMBER

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Texas at Arlington
Grant and Contracts
701 S. Nedderman Dr.
Arlington, TX 76019 -0145

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This grant focuses on the design of advanced control systems for high performance Army vehicles and Autonomous Unmanned Vehicles (UAV/UGV). We focus on the inherent complexity and design challenges of achieving significant performance in short time intervals. Structured Nonlinear Network controllers are designed to significantly improve performance precision and speed of Army systems that have uncertain dynamics, disturbances, and control actuator limitations. On-line adaptive controllers are designed that converge to Optimal Control solutions with guaranteed performance.

15. SUBJECT TERMS
nonlinear adaptive control, neural network control, high performance intelligent control, maneuvering system control, distributed decision and control, autonomous systems control

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Frank Lewis
UU	UU	UU	UU		19b. TELEPHONE NUMBER 817-272-5972

Report Title

Final Report for Discrete Event Supervisory Control and Nonlinear Motion Control for DoD and Industrial Systems

ABSTRACT

This grant focuses on the design of advanced control systems for high performance Army vehicles and Autonomous Unmanned Vehicles (UAV/UGV). We focus on the inherent complexity and design challenges of achieving significant performance in short time intervals. Structured Nonlinear Network controllers are designed to significantly improve performance precision and speed of Army systems that have uncertain dynamics, disturbances, and control actuator limitations. On-line adaptive controllers are designed that converge to Optimal Control solutions with guaranteed performance.

Based on support by National Automotive Center and RDECOM, we also have an initiative in Distributed Control of Networked Heterogeneous Teams. Methods for cooperative control of teams are being developed including discrete event decision & control, trust consensus, and collaborative control.

Significant leveraging funds have been received from NSF, AFOSR, DARPA, and the DoD SBIR Program. This grant gas goals: Goal 1 - Neural Network High Performance Nearly Optimal Control. Goal 2 - Neural Network H-Infinity Structured Output Feedback Control. Goal 3 - Decision and control for distributed heterogeneous teams of autonomous rotorcraft, ground vehicles, and humans.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/25/2011	11.00	Frank. L. Lewis. please see attachment file for list of papers, various journals see attachment please, (01 2010): 0. doi:
08/02/2006	1.00	Murad Abu-Khalaf, Frank L. Lewis. Nearly optimal control laws for nonlinear systems with saturating actuators using a neural network HJB approach, Automatica, ( ): . doi:
08/05/2006	2.00	Jyotirmay Gadewadikar, Frank L. Lewis, Murad Abu-Khalaf. Necessary and Sufficient Conditions for H-Infinity Static Output-Feedback Control, Journal of Guidance, Control, and Dynamics, ( ): . doi:
08/06/2006	3.00	Bruno Borovic, Frank L. Lewis, Dereje Agonafer, ?Edward S. Kolesar, Mohammad Masum Hossain, and Dan O. Popa . Method for Determining a Dynamical State–Space Model for Control of Thermal MEMS Devices, Journal of Microelectromechanical Systems, ( ): . doi:
08/06/2006	4.00	Tao Cheng, Frank L. Lewis, and Murad Abu-Khalaf. A Neural Network Solution for Fixed-Final Time Optimal Control of Nonlinear Systems, , ( ): . doi:
08/06/2006	5.00	B. Borovic, A. Q. Liu, D. Popa, H. Cai and F. L. Lewis. Open-loop versus closed-loop control of MEMS devices: choices and issues, Journal of Micromechanics & Microengineering, ( ): . doi:
08/06/2006	7.00	B. BOROVIC, F.L. LEWIS, W. McCULLEY, Al QUN LIU, E.S. KOLESAR, and D.O. POPA. Control Issues for Microelectromechanical Systems, IEEE Control System Magazine, ( ): . doi:
08/06/2006	8.00	B. Borovic, F. L. Lewis, A. Q. Liu, E. S. Kolesar, and D. Popa. The lateral instability problem in electrostatic comb drive actuators: modeling and feedback control, Journal of Micromechanics & Microengineering, ( ): . doi:
08/06/2006	9.00	S. Bogdan, F.L. Lewis, Z. Kovacic, and J. Mireles. Book published- Manufacturing Systems Control Design: A Matrix Based Approach, , ( ): . doi:
08/06/2006	10.00	M. Abu-Khalaf, J. Huang, and F.L. Lewis. book published- Nonlinear H2/H-Infinity Constrained Feedback Control: A Practical Design Approach Using Neural Networks, , ( ): . doi:

TOTAL: **10**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

(1) Invited Tutorial, Int. Symp. ADP and Reinforcement Learning, Paris, April 2011.
(2) Plenary Speaker, IFAC Workshop on Adaptation and Learning in Control, Antalya, Turkey, August 2010.
(3) Nanyang Technological University, Singapore, distributed control, January 2011.
(4) King Fahd Univ. Petroleum and Minerals, Ehammam, Saudi Arabia, "Approximate Dynamic Programming for Control," May 2011.
(5) South China Univ. Science and Technology, Guangzhou, "Cooperative Control for Netowrked Teams," May 2011.
(6) Invited Speaker, Chinese Academy of Sciences, "Reinforcement Learning for feedback control," Beijing, May 2011.
(7) Plenary Speaker, ISA, "Approximate dynamic programming and cooperative control," Wuhan, China, May 2011.
(8) Plenary Panel Chair, Int. Symposium on Neural Networks, "Future directions of neural networks," Guilin, China, May 2011.

Number of Presentations: 8.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper	
08/06/2006	6.00	Murad Abu-Khalaf, Frank L. Lewis, and Jie Huang. Policy Iterations on the Hamilton-Jacobi-Isaacs Equation for H? State Feedback Control with Input Saturation, IEEE ( )
TOTAL:	**1**	

Number of Manuscripts:

Books

Received	Paper
TOTAL:	

Patents Submitted

Patents Awarded

(1) J. Campos and F.L. Lewis, "Method for Backlash Compensation Using Discrete-Time Neural Networks," U.S. Patent 7,080,055, awarded July 2006.

(2) B. Borovic, F.L. Lewis, A.Q. Liu, and D. Popa, "Systems and Methods for Improved Control of Micro-Electrical-Mechanical Systems (MEMS) Electrostatic Actuator," U.S. Patent 7,548,011, awarded 16 June 2009.

Awards

(1) Distinguished Scholar Professor, Singapore Institute of Manufacturing Technology, SIMTech, A-Star, 2010-2011.
(2) IEEE Region 5 Outstanding Engineering Educator Award, 2010.
(3) UTA Graduate Dean's Excellence in Doctoral Mentoring Award, 2010.
(4) Best Paper Award for Autonomous/Unmanned Vehicles, Army Science Conf. Orlando, 2010. K.G. Vamvoudakis, D.G. Mikulski, G.R. Hudas, F.L. Lewis, and E.Y. Gu, "Distributed games for multi-agent systems: games on communication graphs."
(5) Best Application Paper Award, Asian Control Conference, Taiwan, May 2011. C.K. Pang, J.H. Zhou, Z.W. Zhong, F.L. Lewis, "industrial Fault Detection and Isolation Using Dominant Feature Identification."

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Drew Morgan	0.00	
Matt Middleton	0.50	
Draguna Vrabie	0.50	
Kyriakos Vamvoudakis	0.50	
Chris McMurrough	0.00	
Dariusz Mikulski	0.00	
New Entry	0.00	
FTE Equivalent:	**1.50**	
Total Number:	**7**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
F.L. Lewis	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

NAME
Matt Middleton
Chris McMurrough
Drew Morgan
Total Number: 3

Names of personnel receiving PHDs

NAME
Kyriakos Vamvoudakis
Draguna Vrabie
Total Number: 2

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

(1) With Dr. Greg Hudas, Army RDECOM/TARDEC, Joint research and publications on trust-based control and supervisory decision for networked military teams. Numberous publications have resulted so far, please see list in attached file. We are organizing two special issues of J. Defense Modeling & Simulation together. We won the Best Paper Award for Autonomous Systems at 2010 Army Science Conference.
(2) With Dr. Grant Gerhart, Organizaing special sessions for him and giving invited talks at his conferences. We have organized sessions on Intelligent Behaviors at SPIE Defense Symposium, Orlando, for the past 3 years. These sessions bring together internationally known scientists in Intelligent Control and Autonomous Systems. Participants were: Sylvia Ferrari, Lauta Barnes, Greg Hudas, Richard Garcia, Kevin Moore, Kimon Valavanis, Jagannathan Sarangapani, F.L. Lewis. The papers will be published in 2 special issues of JDMS.
(3) With Dariusz Mikulski, NAC, I am on his PhD committee as co-supervisor with Dr. Edward Gu at Oakland Univ. We are working on distributed decision and trust consensus for networked teams.

Other Collaborations:
(1) My USA MS student Chris McMurrough was selected as an Air Force Summer Scholar last year 2008 and this year 2009 to work with Dr. David Doman at Dr. Siva Banda's USAF Controls Center of Excellence at Wright Patterson AFB. My USA MS student Drew Morgan was selected in 2010 and Isaac Weintraub in 2011.
(2) Worked with DARPA throughan SBIR I from SignalPro, Inc., CEO Chiman Kwan, on reinforcement learning for control of UAV.

Tech Transfer to Industry:
We worked with Singapore Manufacturing Technology Institute to use the results of our ARO research for fault diagnosis in Industrial machines. We won the Best Application Paper Award at 2011 Asian Control Conference.

Technology Transfer

Publications for ARO report between 1 August 2010 – 31 July 2011

Journal Papers

[1] G. Hudas, K.G. Vamvoudakis, D. Mikulski, and F.L. Lewis, "Online Adaptive Learning for Team Strategies in Multi-Agent Systems," J. Defense Modeling and Simulation," to appear, 2011.

[2] C.K. Pang, G. Hudas, M. Middleton, C.V. Le, O.P. Gan, and F.L. Lewis, "Discrete Event Command and Control for Networked Teams with Multiple Military Missions" J. Defense Modeling and Simulation, to appear, 2011.

[3] J.H. Kim and F.L. Lewis, "Model-free H-infinity control design for unknown linear discrete-time systems via Q-learning with LMI," Automatica, vol. 46, no. 8, pp. 1320-1326, Aug. 2010.

[4] K.G. Vamvoudakis and F.L. Lewis, "Multi-Player Non-Zero Sum Games: Online Adaptive Learning Solution of Coupled Hamilton-Jacobi Equations," Automatica, to appear, 2011.

[5] F.L. Lewis and K.G. Vamvoudakis, "Reinforcement learning for partially observable dynamic processes: adaptive dynamic programming using measured output data," IEEE Trans. Systems, Man, And Cybernetics-Part B: vol. 41, no. 1, pp. 14-25, Feb. 2011.

[6] D. Vrabie and F.L. Lewis, "Adaptive dynamic programming for online solution of a zero-sum differential game," *J Control Theory App.*, vol. 9, no. 3, pp. 353–360, 2011.

[7] J.H. Zhou, C.K. Pang, Z.W. Zhong, and F.L. Lewis, "Tool Wear Monitoring Using Acoustic Emissions by Dominant-Feature Identification," IEEE Trans. Instrumentation and Measurement, vol. 60, no. 2, pp. 547-559, February 2011.

[8] J.H. Zhou, C.K. Pang,' F.L. Lewis, and Z.W. Zhong, "Dominant Feature Identification for Industrial Fault Detection and Isolation Applications," Expert Systems With Applications, vol. 38, no. 8, pp. 10676-10684, Aug2011

[9] S. Liu, L. Xie, and F.L. Lewis, "Synchronization of multi-agent systems with delayed input information from neighbors," Automatica, to appear, 2011.

[10] Gang Chen and F.L. Lewis, "Distributed adaptive tracking control for synchronization of unknown networked Lagrangian systems," IEEE Trans. Systems, Man and Cybernetics- Part B, to appear, 2011.

[11] H. Zhang, F.L. Lewis, and Abhijit Das, "Optimal design for synchronization of cooperative systems: state feedback, observer and output feedback," IEEE Trans. Automatic Control, to appear, 2011.

Invited Plenary Talks- Presentations with no publications

1. Invited Tutorial, Int. Symp. ADP and Reinforcement Learning, Paris, April 2011.
2. Plenary Speaker, IFAC Workshop on Adaptation and Learning in Control, Antalya, Turkey, August 2010.
3. Nanyang Technological University, Singapore, distributed control, Jan. 2011.
4. King Fahd Univ. Petroleum and Minerals, Dhammam, Saudi Arabia, "Approximate Dynamic Programming for Control, May 2011.
5. South China Univ. Science and Technology, Guangzhou, "Cooperative Control for Networked Teams," May 2011.
6. Invited Speaker, Chinese Academy of Sciences, "Reinforcement Learning for feedback control, Beijing, May, 2011.
7. Plenary Speaker, ISA, "Approximate dynamic programming and cooperative control," Wuhan, China, May 2011

8. Plenary Panel Chair, Int. Symposium on Neural Networks, “Future directions of neural networks,” Guilin, China, May 2011.

Refereed and Published Conference Papers

[1] K.G. Vamvoudakis, D.G. Mikulski, G.R. Hudas, F.L. Lewis, and E.Y. Gu, “Distributed games for multi-agent systems: games on communication graphs,“ Army Science Conf, paper EO-03, Orlando, 29 Nov- 2 Dec, 2010.

Won the Best Paper Award for Autonomous/Unmanned Vehicles, Army Science Conf. 2010.

[2] D.G. Mikulski, F.L. Lewis, E.Y. Gu, and G.R. Hudas, “Trust dynamics in multi-agent coalition formation,” Proc. SPIE Defense Symposium, Orlando, April 2011.

[3] C.K. Pang, J.H. Zhou, Z.W. Zhong and F.L. Lewis, “Industrial Fault Detection and Isolation Using Dominant Feature Identification,” Proc. Asian Control Conf., pp. 1018-1023, Kaohsiung, Taiwan, May 2011.

Won the Best Application Paper Award at Asian Control Conference, Taiwan, May 2011.

[4] F.L. Lewis and A. Das, “Distributed observer, duality, and optimal regulator design for multi-agent systems, Proc. IEEE Conf. Decision & Control, pp. 7265-7271, Atlanta, Dec. 2010.

[5] G. Chen and F.L. Lewis, “Distributed adaptive controller design for unknown networked Lagrangian systems, Proc. IEEE Conf. Decision & Control, pp, 6698-6703, Atlanta, Dec. 2010.

[6] H. Zhang and F.L. Lewis, “Synchronization of networked higher-order nonlinear systems with unknown dynamics,” Proc. IEEE Conf. Decision & Control, pp. 7129-7134, Atlanta, Dec. 2010.

[7] L. Shuai, L. Xie, and F.L. Lewis, “Synchronization of multi-agent systems with delayed input information from neighbors,” Proc. IEEE Conf. Decision & Control, Atlanta, pp. 4529-4534, Dec. 2010.

[8] A. Gasparri, D. Di Paola, G. Ulivi, D. Naso, F. Lewis, “Decentralized task sequencing and multiple missions control for heterogeneous robotic networks,” Proc. IEEE Int. Conf. Robotics and Automation, 2011, to appear.

[9] Z.Qu, C. Li, F.L. Lewis, “Cooperative control based on distributed estimation of network connectivity,” Proc. American Control Conference, pp. 3441-3446, San Francisco, 2011.

[10] G. Chen and F.L. Lewis, “Synchronizing networked Lagrangian systems via binary control protocols,” Proc. IFAC World Congress, Milan, Italy, Aug. 2011.

[11] A. Gasparri, D. Di Paola, G. Ulivi, D. Naso, F.L. Lewis, “Decentralized task sequencing and multiple mission control for heterogeneous robotic networks,” Proc. Int. Conf. Robotics and Automation, Shanghai, May 2011.

[12] G. Gu, L. Marinovici, and F.L. Lewis, “Consensusability of discrete-time multi-agent systems under state feedback control,” Proc. Chinese Control Conf., Yantai, March 2011.

[13] Z. Qu, C. Li, and F.L. Lewis, "Cooperative Control Based on Distributed Estimation of Network Connectivity,” Proc. American Control Conf., San Francisco, June 2011.

[14] C.K. Pang, J.H. Zhou, Z.W. Zhong, and F.L. Lewis, “Tool Wear Forecast Using Dominant Feature Identification of acoustic emissions,” Proc. IEEE Multi-Conference on Systems and Control, pp. 1063-1068, Tokyo, Sept. 2010.

Books

[1] P. Ballal and F.L. Lewis, *Wireless Sensor Network Design*, VDM Verlag, Saarbrucken, Germany, 2010.

[2] K. Sreenath, M.F. Mysorewala, D.O. Popa, and F.L. Lewis, *Adaptive Sampling with Mobile WSN: Simultaneous robot localisation & mapping of parametric spatio-temporal fields*, Control Engineering Series. IET, 2011.

[3] J. Gadewadikar and F.L. Lewis, *H-Infinity Output-Feedback Control: Application to Unmanned Aerial Vehicles*, Lambert Academic Publishing, Saarbrucken, Germany, to appear 2011.

[4] C.K. Pang, F.L. Lewis, T.H. Lee, and Z.Y. Dong, *Intelligent Diagnosis and Prognosis of Industrial Networked Systems*, CRC Press, Boca Raton, 2011.

Book Chapters

[1] D. Vrabie and F.L. Lewis, "Online Adaptive Optimal Control based on Reinforcement Learning," in *Optimization and Optimal Control: Theory and Applications*, ed. A. Chinchuluun, P.M. Pardalos, et al., pp. 309-324, Springer, Berlin, 2010.

[2] K. Vamvoudakis and F.L. Lewis, "Online gaming: real time solution of nonlinear two-player zero-sum games using synchronous policy iteration," in *Advances in Reinforcement Learning*, ed. A. Mellouk, InTech Publishing, 2011.

[3] A. Das and F.L. Lewis, "Distributed adaptive control for networked multi-robot systems," in *Multi-Robot Systems, Trends and Development*, ed. T. Yasuda, InTech publishing, Rijecka, Croatia, 2011.

[4] F.L. Lewis, "Optimal Control," Chap. 25 in *The Control Handbook*, second edition, W.S. Levine ed., CRC Press, 2011.

[5] D. Vrabie and F.L. Lewis, "Approximate Dynamic programming," Chap. 62 in *The Control Handbook*, second edition, W.S. Levine ed., CRC Press, 2011.

[6] A. Das, F.L. Lewis, and K. Subbarao, "Sliding Mode Approach to Control Quadrotor Using Dynamic Inversion," Robust Control, Book 3, ed. A. Lazinica, InTech publishing, Rijecka, Croatia, 2011.

Journal Special Issues

[1] G. Hudas and F.L. Lewis, "Special Issue on Intelligent Behaviors for Tactical Unmanned Systems," J. Defense Modeling & Simulation, to appear 2011.

[2] S. Ferrari, S. Jagannathan, and F.L. Lewis, "Special Issue on Approximate Dynamic Programming and Reinforcement Learning," Journal of Control Theory and Applications, to appear 2011.