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14. ABSTRACT

Grant objectives are to develop new cooperative control protocols and trust propagation mechanisms for networked teams of nonlinear dynamical systems on communication graphs. We developed a body of knowledge for optimal control and adaptive control on graphs that yields guaranteed performance regardless of communication topology constraints. This year we developed novel adaptive control algorithms for solving optimal control and multi-player team games online in real time. We developed the new concept of Dynamic Graphical Games. These are games for cooperative teams networked on communication graph topologies where the standard definition of Nash equilibrium is of limited use. In military transitions, we worked with D. Doman at WPAFB Control systems Center of Excellence where 3 of our US students have been awarded summer fellowships. We worked with Greg Hudas at US Army TARDEC to develop trust and consensus methods for distributed military teams. In industry dual-use tech transfer, we worked with Singapore Manufacturing Technology Institute in industrial machine tool fault diagnosis. This year we received 3 Best Paper Awards and published 3 books, including Optimal Control 3ed, and 11 journal papers. A patent was submitted.

15. SUBJECT TERMS

Cooperative control, multi-agent systems, distributed trust, networked teams, trust management for networked teams, game theory

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Annual Performance Report to:

Dr. Fariba Fahroo, Program Manager, Dynamics and Control

Grant Title:

  Trust-Based Collaborative Control for Teams on Communication Networks

Grant# AFOSR FA9550-09-1-0278

PI: F.L. Lewis, The University of Texas at Arlington

Reporting Period: 04/01/2011 – 03/31/2012

Changes in research objectives: none

Change in AFOSR program manager: none.

Extensions granted or milestones slipped: none

Contents

1. Annual Accomplishments Summary

The objectives of this grant are to develop new cooperative control protocols and trust propagation mechanisms for networked teams of nonlinear dynamical systems on communication graphs. It is difficult to design guaranteed-performance design control systems for cooperative systems on graphs due to the inherent communication restrictions there. We have developed a body of knowledge for optimal control and adaptive control on graphs that overcomes these problems and results in guaranteed performance regardless of communication topology constraints. This year we further established numerous results concerning cooperative systems and multi-player games. We have developed reinforcement learning adaptive control algorithms for solving optimal control and multi-player team games online using data measured along the system trajectories. This work received the Best Paper Award at IJCNN 2010. We have developed the new concept of Dynamic Graphical Games. These are games for cooperative teams networked on communication graph topologies, where the standard definition of Nash equilibrium is of limited use. A new concept of "Interactive Nash Equilibrium" is defined.

In military transitions, we worked with D. Doman at WPAFB Control Science Center of Excellence where 3 of our US students were awarded summer fellowships over 4 years. A best paper award was received. We worked with Greg Hudas at US Army TARDEC to develop trust and consensus methods for distributed military teams. This work received the Best Paper Award in Autonomous Systems at US Army Science Conference 2010. In industry dual-use tech transfer, we work with Singapore Manufacturing Technology Institute in industrial machine tool fault diagnosis. This work received the Best Application Paper Award at Asian Control Conference 2011.

This year we published 3 books, including *Optimal Control* 3rd edition, 3 journal special issues, and 11 journal papers. Two of these were cited as among the mostly highly cited *Automatica* papers. A patent was submitted based on our AFOSR grant work.

2. Objectives and Annual Technical Accomplishments

Grant Objectives

The Objectives of this grant are to develop new mathematical frameworks for decision-making in autonomous teams that use local communication yet yield global consensus of trust, and to develop novel cooperative motion control laws that yield team-wide desired behavior. Military battlefield teams are heterogeneous networks consisting of interacting humans, ground sensors, and unmanned airborne or ground vehicles. Given the presence of enemy components and the possibility of malicious attacks compromising the security of networked teams, a *consensus* must be reached by the team that determines optimal team strategies and game theoretic solutions online in real-time in changing environments. Biological groups such as flocks, swarms, herds have built-in mechanisms to identify team members and reach synchronized motion.

There are two technical goals, and one technology transfer goal:

Goal 1: New Math Framework for Trust and Motion Consensus in Networked Teams

Goal 2: New Distributed Feedback Control Algorithms for Emergent Team Behavior

Tech. Transfer Goal: Work with Dr. David Doman at Dr. Siva Banda's USAF Control Science Center of Excellence, WPAFB.

A summary of this year's technical accomplishments follows.

Online Learning of Optimal Cooperative Strategies and Game Solutions

In our work with students Draguna Vrabie and K. Vamvoudakis cited below we have developed new algorithms and theory for solving optimal control and game theoretic problems online in real-time using data measured along the system trajectories. We term this Optimal Adaptive Control, and the methods are based on principles of reinforcement learning. These methods solve the Riccati equation or the Hamilton Jacobi design equations online using data measured along the system trajectories. In the linear quadratic game case, for instance, the method learns the coupled Riccati equation solutions online without ever explicitly solving the coupled Riccati equation. In the integral reinforcement learning work of Vrabie, the drift dynamics are not needed, so the method solves the Riccati equation online without knowing the system A matrix.

These optimal adaptive learning techniques have been applied to the control of dynamical systems and also to decision-making in military teams. Optimal adaptive control was given for the single-player optimal control problem for nonlinear CT systems, which includes the LQR case. The method was given for 2-player zero-sum games, which includes H-infinity control, in [4] and c) which won the best paper award at IJCNN Barcelona 2010. It was extended to multiplayer nonzero-sum games in [1], which was listed as a top-cited *Automatica* paper. The book [2] containing all these results is under contract to IET Press.

Transition to Military Applications. With Greg Hudas and D. Mikulski at TARDEC/RDECOM, we have also applied these reinforcement learning techniques to decision and control in military teams. During mission execution in military applications, the TRADOC Pamphlet 525-66 "Battle Command and Battle Space Awareness Capabilities" prescribe expectations that networked teams will perform in a reliable manner under changing mission requirements and changing team and individual objectives. Strategies for team decision problems can be formulated as optimal control problems or *N*-player games (zero-sum or non-zero sum). These problems are normally solved off-line by solving associated matrix equations such as the coupled Riccati equations or coupled Hamilton-Jacobi equations. However, using that approach, players cannot change their objectives online in real time without calling for a completely new off-line solution for the new strategies.

With Greg Hudas and D. Mikulski at TARDEC/RDECOM, we have developed methods for learning optimal team strategies online in real time as team dynamical play unfolds. See work with Hudas and Mikulski cited below. This allows the objectives and costs of multi-agent teams to change in real-time as the agents learn and the game unfolds. This allows for truly dynamical team decisions where objective functions can change in real time and the system dynamics can be time-varying. The paper b) won the 2010 Army Science Conference Best Paper Award for Autonomous Systems. The journal special issue [2] came out of this work.

Dynamic Graphical Games for Networked Cooperative Systems.

We have defined a new type of differential game for cooperative networked systems on communication graphs known as a *dynamic graphical game* [18]. In graphical games, each player interacts only with his neighbors in a graph topology. It is shown that the standard Nash definition is of limited use for networked cooperative systems and a new definition is given-Interactive Global Nash Equilibrium. The local concept of an agent's best response to its neighbors is defined. Methods are given for solving graphical games online in real time using data measured along the system trajectories as agents compete and cooperate during the game.

This allows the performance indices of the agents to change in real-time as agents learn and the game unfolds.

Optimal and Adaptive Control for Synchronization of Multi-Agent Systems

We have developed new methods for control system design for synchronization in distributed multi-agent system. These methods solve the well-known problem of interaction between the controller design and the graph topology constraints. In work with student H. Zhang below it was shown that optimal design of the controller of each agent results in guaranteed synchronization on any strongly connected graph. In work with H. Zhang and student Abhijit Das a new family of adaptive controllers was developed for multi-agent systems that synchronizes cooperative systems with different unknown nonlinear dynamics. In work with Gang Chen cooperative controllers were designed for Langrangian cooperative systems on weakly connected graph topologies. The paper [2] was cited as the 2nd top referenced paper in Automatica during July-Sept. 2011.

Transition to Military Applications. Trust for Coalition Formation in Teams

In work with TARDEC/RDECOM engineers Dr. Greg Hudas and Dariusz Mikulski, we worked on trust propagation in teams as a basis for computing incentives for formation of coalitions. Trust allows team players to have confidence in other members but also opens one to a greater possibility of harm if other agents do not meet agreements. Therefore, we have defined a payoff for coalition formation called trust synergy and a penalty called trust liability. The balance between trust synergy and trust liability determines the evolution of coalitions. Our paper b) won the Best Paper Award in Autonomous Systems at the 2010 Army Science Conference. Also in this series are the journal paper [10] and the special issue [2].

3. Transitions and Technology Transfer

Transitions with WPAFB Controls Center of Excellence

In USAF transition we work with Dr. David Doman at Dr. Siva Banda's Control Science Center of Excellence at WPAFB. Three of our MS students have received the USAF Summer Fellowship to study with Dr. David Doman since 2008. MS student Chris McMurrough worked with Dr. Doman during 2008 and 2009. His project was to design hardware boards for interfacing computers and rotorcraft into the USAF micro-air vehicle test bed. His paper with D. Doman won the Multicore Graphical Design Achievement Award at National Instruments Week, Austin, Aug. 2009. MS student Drew Morgan received the USAF Summer Fellowship to study at WPAFB in 2010, and Isaac Weintraub in 2011.

Secondary Transition Third Partner Relevance

We have strong connections with Dr Greg Hudas at *US Army RDECOM* and are working with him on trust propagation and multi-player games for cooperative teams on networks. Based on work described above, several joint papers cited below have resulted and a journal special issue in J. Defense and Military Simulation [2]. RDECOM PhD student, Dariusz Mikulski, is being co-advised by the PI. We won the Best Paper Award for our joint work b) on multi-agent team games at Army Science Conference, 2010.

Dual Use Tech Transfer to Industry

We work with Singapore Manufacturing Technology Institute SIMTech to transition decision and control results from our AFOSR grant to industrial machine tool monitoring and fault diagnosis. The cited papers of C.K. Pang below are the result. The paper a) won the Best Paper Award at the 2011 Asian Control Conference. The book [5] resulted from this collaboration.

DARPA Contract for Reinforcement Learning Control for UAV

We worked with DARPA through an SBIR I from SignalPro, Inc., CEO Chiman Kwan, on reinforcement learning for control of UAV. This transitions our AFOSR results to UAV control. We developed advanced nonlinear controllers for a quadrotor that learn optimal control solutions through adaptive control online learning techniques based on principles of reinforcement learning.

4. New Discoveries: Patent Submitted

K. Vamvoudakis, D. Vrabie, F.L. Lewis, "Method for Learning Solutions to Multi-Player Games in Real-Time Using Integral Reinforcement Learning," U.S. Patent Disclosure, submitted, 2012.

5. Recent Best Paper Awards

a)   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.

b)   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.

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

c)   D. Vrabie and F.L. Lewis, "Adaptive Dynamic Programming Algorithm for Finding Online the Equilibrium Solution of the Two-Player Zero-Sum Differential Game," Proc. Int. Joint Conf. Neural Networks, pp. 1-8, Barcelona, July 2010.

   This paper won the IJCNN 2010 Best Paper Award.

6. Archival Publications during reporting period

Books Published or Accepted this year only

[1]   F.L. Lewis, D. Vrabie, and V. Syrmos, *Optimal Control*, third edition, John Wiley and Sons, New York, 2012.

[2]   D. Vrabie, K. Vamvoudakis, and F.L. Lewis, *Optimal Adaptive Control and Differential Games by Reinforcement Learning Principles,* IET Press, to appear.

[3]   F.L. Lewis and Derong Liu, editors, *Reinforcement Learning and Approximate Dynamic Programming for Feedback Control,* IEEE Press, Computational Intelligence Series, to appear.

[4]   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.

[5]   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.

Journal Special Issues Published or Accepted this year only

[1] S. Ferrari, S. Jagannathan, and F.L. Lewis, "Special Issue on Approximate Dynamic Programming and Reinforcement Learning," Journal of Control Theory and Applications, vol. 9, no. 3, Aug. 2011.

[2] G. Hudas, D. Mikulski, and F.L. Lewis, "Special Issue on Intelligent Behaviors for Tactical Unmanned Systems," J. Defense Modeling & Simulation, vol. 9, no. 1, Jan. 2012

[3] L. Zhang, H. Gao, and F.L. Lewis, Special Section on "Advances in Theories and Industrial Applications of Networked Control Systems," IEEE Transactions on Industrial Informatics, to appear 2012.

Book Chapters Published or Accepted this year only

[1] 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.

[2] 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.

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

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

[5] A. Das, F.L. Lewis, and K. Subbarao, "Sliding Mode Approach to Control Quadrotor Using Dynamic Inversion," in Challenges and Paradigms in Applied Robust Control, ed. A. Batroszewicz, InTech publishing, Rijecka, Croatia, November 2011.

[6] K.G. Vamvoudakis and F.L. Lewis, "Online Adaptive Learning Solution of Multi-Agent Differential Graphical Games," in "Frontiers in Advanced Control Systems", ed. A. Lazinica, Intech Publishing, Rijeka, Croatia, to appear.

Journal Papers Published or Accepted this year only

[1] K.G. Vamvoudakis and F.L. Lewis, "Multi-Player Non-Zero Sum Games: Online Adaptive Learning Solution of Coupled Hamilton-Jacobi Equations," Automatica, vol. 47, pp. 1556-1569, 2011.

This paper was listed as the 17th most read Automatica article of July-Sept. 2011.

[2] Shaui Liu, L. Xie, and F.L. Lewis, "Synchronization of multi-agent systems with delayed control input information from neighbors," Automatica, vol. 47, pp. 2152-2164, October 2011.

This paper was listed as the 2nd most read Automatica article of July-Sept. 2011.

[3] 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, 2011.

[4] 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.

[5] Gang Chen and F.L. Lewis, "Robust consensus of multiple inertial agents with coupling delays and variable topologies," Int. Journal of Robust and Nonlinear Control, vol. 21, pp. 666-685, 2011.

[6] Gang Chen and F.L. Lewis, "Leader-following control for multiple inertial agents," J. Robust and Nonlinear Control, vol. 21, pp. 925-942, 2011.

[7] 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, vol. 41, no. 3, pp. 805-816, June 2011.

[8]   Gang Chen, F.L. Lewis, and L. Xie, "Finite-time distributed consensus via binary control protocols," Automatica, vol. 47, pp. 1962-1968, 2011.

[9]   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, vol. 56, no. 8, pp. 1948-1952, August 2011.

[10]   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," vol. 9, no. 1, pp. 59-69, Jan. 2012.

[11]   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, Aug. 2011.

[12]   Gang Chen and F.L. Lewis, "Cooperative controller design for synchronization of networked Lagrangian systems," J. Robust and Nonlinear Control, to appear, 2012.

[13]   Gang Chen and F.L. Lewis, "Coordination of networked systems on digraphs with multiple leaders via pinning control," Int. J. Systems Science, to appear, 2012.

[14]   Abhijit Das and F.L. Lewis, "Cooperative adaptive control for synchronization of second-order systems with unknown nonlinearities," Int. Journal of Robust and Nonlinear Control, to appear 2012.

[15]   H. Zhang, F.L. Lewis, and Z. Qu, "Lyapunov, Adaptive, and Optimal Design Techniques for Cooperative Systems on Directed Communication Graphs," IEEE Trans. Industrial Electronics, to appear, 2012.

[16]   H. Zhang and F.L. Lewis, "Adaptive cooperative tracking control of high-order nonlinear systems with unknown dynamics, Automatica, to appear, 2012.

[17]   H. Xu, S. Jagannathan, and F.L. Lewis, "Stochastic Optimal Control of Unknown Linear Networked Control System in the Presence of Random Delays and Packet Losses," Automatica, to appear, 2012.

[18]   K.G. Vamvoudakis and F.L. Lewis, "Multi-Agent Differential Graphical Games: Policy Iteration and Online Adaptive Learning," Automatica, to appear, 2012.

[19]   Guoxiang Gu, L. Maronovici, and F.L. Lewis, "Consensusability of discrete-time dynamic multi-agent systems," IEEE Trans. Automatic Control, to appear, 2012.

[20]   C.K. Pang, S.T. Ng, F.L. Lewis, and T.H. Lee, "Managing complex mechatronics R&D: a systems design approach," IEEE Trans. Systems, Man, Cybernetics, Part A, to appear, 2012.

[21]   C. Du, J. Mou, S. Liu, J. Zhang, and F.L. Lewis, "Structure Crack Identification Based on Surface-mounted Active Sensing Network With Time-domain Feature Extraction and Neural Network," Sensors & Transducers Journal, to appear, 2012.

Conference Papers, Fully refereed and published in Proceedings this year only

[22]   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.

[23]   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.

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

[25]   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.

[26]   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.

[27]   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.

[28]   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.

[29]   K.G. Vamvoudakis and F.L. Lewis, "Multi-agent differential graphical games," Proc. Chinese Control Conf., pp. 4932-4939, Yantai, China, July, 2011.

[30]   K.G. Vamvoudakis and F.L. Lewis, "Policy iteration algorithm for distributed networks and graphical games," Proc. IEEE Conf Decision & Control, pp. 128-135, Orlando, Fla, Dec. 2011.

[31]   K. Vamvoudakis, D. Vrabie, and F.L. Lewis, "Online Adaptive Learning of Optimal Control Solutions Using Integral Reinforcement Learning," Proc. IEEE Symp. ADPRL, Paris, 11-15 April 2011.

[32]   E. Stingu and F.L. Lewis, "An Approximate Dynamic Programming Based Controller Implementation for an Underactuated 6DoF Quadrotor," Proc. IEEE Symp. ADPRL, 11-15 Paris, April 2011.

[33]   K. Vamvoudakis and F.L. Lewis, "Online Learning Solution of Coupled Hamilton-Jacobi and Coupled Riccati Equations," Proc. IEEE Multi-conference on Systems and Control, Denver, CO, Sept. 2011.

[34]   S.G. Khan, G. Herrmann, F.L. Lewis, T. Pipe, and C. Melhuish, "A novel Q-learning based Cartesian model reference compliance controller implementation for a humanoid robotic arm," Proc. IEEE Int. Conf. Robotics, Automation and Mechatronics, CIS-RAM 2011, paper 24, Qingdao, China, Sept., 2011.

[35]   K.Vamvoudakis and F.L. Lewis, "Policy Iteration Algorithm for Distributed Networks and Graphical Games," Proc. IEEE Conf. Decision and Control, Orlando, Dec. 2011.

[36]   C.K. Pang, T.S. Ng, F.L. Lewis, T.H. Lee, "A systems design approach to manage mechatronics R&D," Proc. IEEE Int. Conf. Robotics, Automation and Mechatronics, CIS-RAM 2011, pp. 136-141, Qingdao, China, Sept., 2011.

[37]   C.K. Pang, C.V. Le, O.P. Gan, X.M. Chee, M. Luo, C.H. Leng, F.L. Lewis, "Intelligent energy audit and machine management for energy-efficient manufacturing," Proc. IEEE Int. Conf. Robotics, Automation and Mechatronics, CIS-RAM 2011, pp. 142-147, Qingdao, China, Sept., 2011.

[38]   C.V. Le, C.K. Pang, F.L. Lewis, O.P. Gan, H.L. Chan, "Intelligent Dynamic Resource Assignment for Energy-Efficiency in Industrial Stamping Machines," Proc. IEEE Industrial Electronics Society (IECON 2011), pp. 4131-4136, Melbourne, Nov. 2011.

7. Awards

PI Awards This Year

Visiting Scholar Fellow, Singapore Institute of Manufacturing Technology, SIMTech, A-Star, 2011.

Four International Invited Plenary Talks in 16 months.

Student Awards Throughout Grant Duration

Chris McMurrough, MS student. "Micro Flapping Air Vehicle." Received the Air Force Summer Fellowship to work at Wright Patterson AFB with Dr. David Doman and Dr. Siva Banda, in 2009.

UTA Honors College Fellowship, 2008, 2009.

C. McMurrough, K. French, D. Doman, "Real-Time MAV Flight Control System Testbed"

This paper won the Multicore Graphical Design Achievement Award at National Instruments Week, Austin, Aug. 2009

Drew Morgan. MS student. "Minirobot Designs for Swarm Motions." Received the Air Force Summer Fellowship to work at Wright Patterson AFB with Dr. David Doman and Dr. Siva Banda, in 2010.

Isaac Weintraub. MS student. "Micro Flapping Air Vehicle." Received the Air Force Summer Fellowship to work at Wright Patterson AFB with Dr. David Doman and Dr. Siva Banda, in 2011.

8. Students Supported

PhD students graduated this year

1. K. Vamvoudakis, *Online Learning Algorithms For Differential Dynamic Games And Optimal Control*, May 2011.

   Best Paper Award for Autonomous/Unmanned Vehicles, Army Science Conf, Orlando, 29 Nov- 2 Dec, 2010.

2. E. Stingu, Intelligent Control and Cooperation for Mobile Robots, December 2011.

Students Supported During Duration of Grant

(AFOSR and leveraging funds)

Draguna Vrabie, female student, received PhD at UTA in December 2009.
        Senior Research Scientist, United Technologies Research Center, East Hartford, CT

Abhijit Das, received PhD at UTA in August 2010.
        Now at Caterpillar, Inc.

Kyriakos Vamvoudakis, received PhD at UTA in May 2011.
        Center for Control, Dynamical-Systems, and Computation (CCDC), UC Santa Barbara

E. Stingu, received PhD at UTA in December 2011.
        Now at UAV Design

Kristian Movric, PhD student at UTA.

M. Aurangzeb, PhD student at UTA.

M. Abouheaf, PhD student at UTA.

US Citizen Students: All have worked with Dr Siva Banda's group at WPAFB.
Chris McMurrough, received MS Degree at UTA May 2010.
Drew Morgan, received MS degree at UTA in May 2011.
Isaac Weintraub, MS student at UTA.