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6. AUTHORS
Vijay Kumar, Francesco Bullo, Daniel Koditschek, Ali Jadbabaie, A. Stephen Morse, George Pappas, Daniela Rus, S. Shankar Sastry, David Skelly

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14. ABSTRACT
The SWARMS project brings together experts in artificial intelligence, control theory, robotics, systems engineering and biology with the goal of understanding swarming behaviors in nature and applications of biologically-inspired models of swarm behaviors to large networked groups of autonomous vehicles. The main goal is to develop a framework and methodology for the analysis of swarming behavior in biology and the synthesis of bio-inspired swarming behaviors for engineered systems. We are interested in such questions as: Can large numbers

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Report Title

SWARMS: Scalable sWarms of Autonomous Robots and Mobile Sensors

ABSTRACT

The SWARMS project brings together experts in artificial intelligence, control theory, robotics, systems engineering and biology with the goal of understanding swarming behaviors in nature and applications of biologically-inspired models of swarm behaviors to large networked groups of autonomous vehicles. The main goal is to develop a framework and methodology for the analysis of swarming behavior in biology and the synthesis of bio-inspired swarming behaviors for engineered systems. We are interested in such questions as: Can large numbers of autonomously functioning vehicles be reliably deployed in the form of a “swarm” to carry out a prescribed mission and to respond as a group to high-level management commands? Can such a group successfully function without a designated leader, with limited communications between its members, and with dynamically changing “roles” for its members? Is there a hierarchy of “compatible” models appropriate to swarming/schooling/flocking which is rich enough to explain these behaviors at various “resolutions” ranging from aggregate characterizations of emergent behavior to detailed descriptions which model individual vehicle dynamics?

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
01/07/2013	45.00	Brian J. Julian, Mac Schwager, M. Angermann, D. Rus. Eyes in the Sky: Decentralized Control for the Deployment of Robotic Camera Networks, Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2158377
01/07/2013	46.00	H. Chung, E. Polak, S. Sastry. On the Use of Outer Approximations as an External Active Set Strategy, , (02 2010): 0. doi: 10.1007/s10957-010-9655-8
10/24/2011	1.00	J. Fink, N. Michael, S. Kim, V. Kumar. Planning and control for cooperative manipulation and transportation with aerial robots, The International Journal of Robotics Research, (09 2010): 0. doi: 10.1177/0278364910382803
10/24/2011	2.00	Edward B Steager, Mahmut Selman Sakar, Dal Hyung Kim, Vijay Kumar, George J Pappas, Min Jun Kim. Electrokinetic and optical control of bacterial microrobots, Journal of Micromechanics and Microengineering, (03 2011): 0. doi: 10.1088/0960-1317/21/3/035001
10/24/2011	3.00	Mahmut Selman Sakar, E. B. Steager, Dal Hyung Kim, A. Agung Julius, M. Kim, V. Kumar, G. J. Pappas. Modeling, control and experimental characterization of microbiorobots, The International Journal of Robotics Research, (01 2011): 0. doi: 10.1177/0278364910394227
10/24/2011	4.00	S. Berman, Q. Lindsey, M. S. Sakar, V. Kumar, S. C. Pratt. Experimental Study and Modeling of Group Retrieval in Ants as an Approach to Collective Transport in Swarm Robotic Systems, Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2111450
10/24/2011	11.00	Jonathan Fink, Alejandro Ribeiro, Vijay Kumar. Robust Control for Mobility and Wireless Communication in Cyber–Physical Systems With Application to Robot Teams, Proceedings of the IEEE, (8 2011): 0. doi: 10.1109/JPROC.2011.2161427
10/24/2011	12.00	G. Notarstefano, F. Bullo. Distributed Abstract Optimization via Constraints Consensus: Theory and Applications, IEEE Transactions on Automatic Control, (08 2011): 0. doi: 10.1109/TAC.2011.2164020
10/24/2011	13.00	Stephen L. Smith, Francesco Bullo, Shaunak D. Bopardikar. On vehicle placement to intercept moving targets, Automatica, (9 2011): 0. doi: 10.1016/j.automatica.2011.06.010
10/24/2011	14.00	F. Bullo, E. Frazzoli, M. Pavone, K. Savla, S. L. Smith. Dynamic Vehicle Routing for Robotic Systems, Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2158181
10/24/2011	17.00	A Tahbaz-Salehi, A Jadbabaie. Distributed Coverage Verification in Sensor Networks Without Location Information, IEEE Transactions on Automatic Control, (08 2010): 0. doi: 10.1109/TAC.2010.2047541
10/24/2011	20.00	Ji Liu, Shaoshuai Mou, A. Stephen Morse, Brian D. O. Anderson, Changbin Yu. Deterministic Gossiping, Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2159689
10/24/2011	21.00	M. M. Zavlanos, M. B. Egerstedt, G. J. Pappas. Graph-Theoretic Connectivity Control of Mobile Robot Networks, Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2157884
10/24/2011	22.00	M. Schwager, D. Rus, J.-J. Slotine. Unifying geometric, probabilistic, and potential field approaches to multi-robot deployment, The International Journal of Robotics Research, (09 2010): 0. doi: 10.1177/0278364910383444
10/24/2011	26.00	David K. Skelly, Michael F. Benard. Mystery unsolved: missing limbs in deformed amphibians, Journal of Experimental Zoology Part B: Molecular and Developmental Evolution, (5 2009): 0. doi: 10.1002/jez.b.21330

10/24/2011 27.00 Nathan Michael, Vijay Kumar. Control of Ensembles of Aerial Robots,
Proceedings of the IEEE, (09 2011): 0. doi: 10.1109/JPROC.2011.2157275

12/21/2012 29.00 Stephen L. Smith, Francesco Bullo. The dynamic team forming problem: Throughput and delay for unbiased policies,
Systems & Control Letters, (10 2009): 0. doi: 10.1016/j.sysconle.2009.07.001

12/21/2012 30.00 Francesco Bullo, Ruggero Carli, Paolo Frasca. Gossip Coverage Control for Robotic Networks: Dynamical Systems on the Space of Partitions,
SIAM Journal on Control and Optimization, (01 2012): 0. doi: 10.1137/100806370

12/21/2012 33.00 Antonis Papachristodoulou, Ali Jadbabaie, Ulrich Mu?nz. Effects of Delay in Multi-Agent Consensus and Oscillator Synchronization,
IEEE Transactions on Automatic Control, (06 2010): 0. doi: 10.1109/TAC.2010.2044274

12/21/2012 32.00 Antonis Papachristodoulou, Ali Jadbabaie. Delay Robustness of Nonlinear Internet Congestion Control Schemes,
IEEE Transactions on Automatic Control, (06 2010): 0. doi: 10.1109/TAC.2010.2044262

12/21/2012 34.00 A. Jadbabaie, A. Tahbaz-Salehi. Consensus Over Ergodic Stationary Graph Processes,
IEEE Transactions on Automatic Control, (01 2010): 0. doi: 10.1109/TAC.2009.2034054

12/21/2012 35.00 M.M. Zavlanos, H.G. Tanner, A. Jadbabaie, G.J. Pappas. Hybrid Control for Connectivity Preserving Flocking,
IEEE Transactions on Automatic Control, (12 2009): 0. doi: 10.1109/TAC.2009.2033750

12/21/2012 36.00 G.L. Mariottini, F. Morbidi, D. Prattichizzo, N. Vander Valk, N. Michael, G. Pappas, K. Daniilidis. Vision-Based Localization for Leader–Follower Formation Control,
IEEE Transactions on Robotics, (12 2009): 0. doi: 10.1109/TRO.2009.2032975

12/21/2012 37.00 S. Berman, A. Halasz, M.A. Hsieh, V. Kumar. Optimized Stochastic Policies for Task Allocation in Swarms of Robots,
IEEE Transactions on Robotics, (08 2009): 0. doi: 10.1109/TRO.2009.2024997

12/21/2012 38.00 J.-Y. Sul, C.-w. K. Wu, F. Zeng, J. Jochems, M. T. Lee, T. K. Kim, T. Peritz, P. Buckley, D. J. Cappelleri, M. Maronski, M. Kim, V. Kumar, D. Meaney, J. Kim, J. Eberwine. Transcriptome transfer produces a predictable cellular phenotype,
Proceedings of the National Academy of Sciences, (04 2009): 0. doi: 10.1073/pnas.0902161106

12/21/2012 39.00 M. Kumar, D.P. Garg, V. Kumar. Segregation of Heterogeneous Units in a Swarm of Robotic Agents,
IEEE Transactions on Automatic Control, (03 2010): 0. doi: 10.1109/TAC.2010.2040494

12/21/2012 40.00 David J. Cappelleri, Girish Krishnan, Charles Kim, Vijay Kumar, Sridhar Kota. Toward the Design of a Decoupled, Two-Dimensional, Vision-Based ?N Force Sensor,
Journal of Mechanisms and Robotics, (2010): 0. doi: 10.1115/1.4001093

12/21/2012 41.00 Daniel Mellinger, Quentin Lindsey, Vijay Kumar, Nathan Michael. The GRASP Multiple Micro-UAV Testbed,
IEEE Robotics & Automation Magazine, (09 2010): 0. doi: 10.1109/MRA.2010.937855

12/21/2012 42.00 David K. Skelly, Susan R. Bolden, Kirstin B. Dion. Intersex Frogs Concentrated in Suburban and Urban Landscapes,
EcoHealth, (09 2010): 0. doi: 10.1007/s10393-010-0348-4

12/21/2012 43.00 Earl E. Werner, Rick A. Relyea, Kerry L. Yurewicz, David K. Skelly, Christopher J. Davis. Comparative landscape dynamics of two anuran species: climate-driven interaction of local and regional processes,
Ecological Monographs, (08 2009): 0. doi: 10.1890/08-1047.1

12/21/2012 44.00 Ming Cao, A. Stephen Morse. Dwell-time switching,
Systems & Control Letters, (01 2010): 0. doi: 10.1016/j.sysconle.2009.11.007

TOTAL: **31**

Number of Papers published in peer-reviewed journals:

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

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Skelly, D. K. and L. K. Freidenburg. in press. Evolutionary responses to climate change. Encyclopedia of Life Sciences. Wiley Blackwell.
2.J. Liu, A. S. Morse, B. D. O. Anderson, and C. Yu. The contraction coefficient of a complete gossip sequence. In X. Hu and B. Ghosh, editors, Three Decades of Progress in Control Sciences. Springer, 2010. to appear.
3. B. D. O. Anderson, C. Yu, and A. S. Morse. Convergence of periodic gossiping algorithms. In S. Hara, Y. Ohta, and J. C. Willems, editors, Perspectives in Mathematical System Theory, Control, and Signal Processing, pages 127–138. Springer, 2010.
4.. Francesco Bullo, 2009: UC San Diego (ITA Workshop), University of Liege (Belgium), University of Washington, Carnegie Mellon University, Block Island Workshop on Swarming, University of Lecce (Italy), University of Stuttgart (Germany, NESTCOC Symposium), ETH Z\"urich (Switzerland)
5. Francesco Bullo, 2010: UC San Diego (ITA Workshop), University of New Mexico, Los Alamos National Laboratory, Massachusetts Institute of Technology, ARL Adelphi Laboratory Center, California Institute of Technology, University of Southern California, University of Illinois at Urbana-Champaign, Northwestern University, University of Illinois at Chicago, University of Cagliari (Italy), CNRS Supelec (France)
6. Ali Jadbabaie: Plenary Speaker at the 2011 Chinese Control Conference (CCC 2011, scheduled)
7. Ali Jadbabaie: Semi-plenary speaker at First IFAC Workshop on Networked Control Systems, Venice, Italy, September 2009
8, Ali Jadbabaie: Semi-plenary speaker at the IEEE Conference on Decision and Control, Shanghai, China, December 2009
9. Ali Jadbabaie: Plenary Speaker, Georgia Tech Student Conference, April 2010
10. Ali Jadbabaie: Plenary Speaker, Belgian Bi-annual Conference on Dynamics, Control and Optimization, Ghent, Belgium, May 2010
11. Ali Jadbabaie: Invited Speaker and Symposium Co-organizer, Foundations of Computational Math, FOCM 2011
12. Ali Jadbabaie: University of Chicago Math Department Colloquium, September 2010 UT Austin EE Seminar, September 2010
13. Ali Jadbabaie: Harvard-Air Force Workshop on Complex Networks, Novembers 2009
14. Ali Jadbabaie: IEEE CDC Workshop on Network Science December 2009
15. Vijay Kumar: “Three Studies in Multi-Robot Systems: Ensemble Control, Maintaining Con- nectivity, and Aerial Manipulation,” Australian Centre for Field Robotics, Uni- versity of Sydney, September 2009.
16. Vijay Kumar: Booze Allen Hamilton Distinguished Lecturer, Department of Electrical and Computer Engineering, University of Maryland, September 2009.
17. Vijay Kumar: Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, October 2010.
18. Vijay Kumar: Center for Information and Systems Engineering, Boston University, January 2010.
19. Vijay Kumar: Keynote, Mechanisms and Robotics, ASME International Design Engineering Technical Conferences, Montreal, CA.
20. Vijay Kumar: Quentin Lindsey, Mike Shomin, Spring Berman, Vijay Kumar, and Stephen Pratt. Bio-Inspired Approaches to Cooperative Manipulation and Transport by Robots. Conference on Social Biomimicry: Insect Societies and Human Design. Feb. 18-20, 2010, Arizona State University, Tempe, AZ
21. Vijay Kumar: ICRA 2010 Workshop on Mobile Microrobots: Biosensing and Actuation for Microbiorobots, M. Selman Sakar
22. David Skelly: Ecology and Evolution, University of California Davis
23. David Skelly: Department of Biology, Reed College
24. David Skelly: Cornell Herpetological Society, Cornell University
25. David Skelly: Hudson River Environmental Society
26. David Skelly: Lecturer, Assoc. of Yale Alumni Educational Travel, Sea of Cortez
27. David Skelly: Pomperaug River Watershed Coalition, Southbury, Connecticut
28. David Skelly: Keynote Speaker, Guilford Land Trust Annual Meeting
29. David Skelly: Keynote Speaker, Simsbury Land Trust Annual Meeting
30. A. S. Morse: “The Contraction Coefficient of a Complete Gossip Sequence” Workshop on a Celebration of the Field of Systems and Control, Stockholm September 11, 2009
31. A. S. Morse: “Formation Control” Symposium on Open and Interconnected Systems Modeling and Control, Bruges Belgium, September 16, 2009
32. S. Morse: “Convergence Rates for Deterministic Gossip Sequences” Natural Algorithms Workshop, Princeton University, November 3, 2009.
33. D. O. Anderson: “Deterministic Multi-Gossiping Algorithms” Symposium on Systems, Control and Signal Processing, Kyoto University, March 31, 2010
34. S. Morse: “Deterministic Gossiping” Symposium on Systems, Control and Signal Processing, Kyoto University, March 31, 2010 31. Daniela Rus: Cooperative construction with Swarms, ICRA 2010 workshop on Formal methods for robotics and automation.
35. Ali Jadbabaie: Plenary Speaker at the 2011 Chinese Control Conference (CCC 2011)
36. Ali Jadbabaie: Invited Speaker and Symposium Co-organizer, Foundations of Computational Math, FOCM 2011

Number of Presentations: 3.00

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
10/24/2011	8.00	Mahmut Selman Sakar, Edward B. Steager, Anthony Cowley, Vijay Kumar, George J. Pappas. Wireless manipulation of single cells using magnetic microtransporters, 2011 IEEE International Conference on Robotics and Automation (ICRA). 2011/05/09 00:00:00, Shanghai, China. : ,
10/24/2011	9.00	Spring Berman, Vijay Kumar, Radhika Nagpal. Design of control policies for spatially inhomogeneous robot swarms with application to commercial pollination, 2011 IEEE International Conference on Robotics and Automation (ICRA). 2011/05/09 00:00:00, Shanghai, China. : ,
10/24/2011	10.00	Mac Schwager, Nathan Michael, Vijay Kumar, Daniela Rus. Time scales and stability in networked multi-robot systems, 2011 IEEE International Conference on Robotics and Automation (ICRA). 2011/05/09 00:00:00, Shanghai, China. : ,
10/24/2011	15.00	Fabio Pasqualetti, Antonio Franchi, Francesco Bullo. On optimal cooperative patrolling, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,
10/24/2011	16.00	Joseph W. Durham, Ruggero Carli, Francesco Bullo. Pairwise optimal discrete coverage control for gossiping robots, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,
10/24/2011	18.00	Usman A. Khan, Soummya Kar, Ali Jadbabaie, Jose M. F. Moura. On connectivity, observability, and stability in distributed estimation, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,
10/24/2011	19.00	Victor M. Preciado, Alireza Tahbaz-Salehi, Ali Jadbabaie. On asymptotic consensus value in directed random networks, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,
10/24/2011	23.00	A Breitenmoser, J Metzger, R Siegwart, D Rus. Distributed Coverage Control on Surfaces in 3D Space, 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010). 2010/10/18 00:00:00, Taipei. : ,
10/24/2011	24.00	A Bolger, M Faulkner, D Stein, L White, Seung-kook Yun, D Rus. Experiments in decentralized robot construction with tool delivery and assembly robots, 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010). 2010/10/18 00:00:00, Taipei. : ,
10/24/2011	25.00	Humberto Gonzalez, Ram Vasudevan, Maryam Kamgarpour, S. Shankar Sastry, Ruzena Bajcsy, Claire Tomlin. A numerical method for the optimal control of switched systems, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,
10/24/2011	28.00	S. Mou, C. Yu, B. D. O. Anderson, A. S. Morse. Deterministic gossiping with a periodic protocol, 2010 49th IEEE Conference on Decision and Control (CDC). 2010/12/15 00:00:00, Atlanta, GA, USA. : ,

TOTAL: **11**

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

(d) Manuscripts

Received		Paper
12/21/2012	31.00	Shaunak D. Bopardikara, Stephen L. Smith, Francesco Bulloa. On vehicle placement to intercept moving targets, Automatica (09 2011)
TOTAL:		**1**

Number of Manuscripts:

Books

Received	Paper
TOTAL:	

Patents Submitted

Patents Awarded

Awards

1. Francesco Bullo: Plenary Speaker: 3rd IEEE Multi-Conference in Systems and Control, Saint Petersburg, Russia, Jul 2009

2. Francesco Bullo: Visiting Professor, University of Cagliari, Jul 2010
3. Francesco Bullo: Best Student Paper Award, ACC 2010
4. Francesco Bullo: IEEE Fellow, Class of 2010
5. Francesco Bullo: Article selection for inclusion in SIGEST section of SIAM Review, Mar 2009
6. Francesco Bullo: Outstanding Paper Award, IEEE Control Systems Magazine, 2008
7. N. Michael, J. Fink, V. Kumar. Best Student Paper Award, RSS 2009.
8. Daniela Rus: Elected Fellow of IEEE and AAAI; Best Paper Finalist at IROS 2009
9. Kumar, Advisor to Best Paper Award, Robotics Science and Systems, 2009.
10. Kumar, Advisor to Best Student Paper Award, Distributed Autonomous Robotic Systems, 2010.
11. Kumar, Best Paper Award, IEEE Int. Conference on Robotics and Automation, 2011.
12. Kumar, Best Paper Award, Robotics Science and Systems, 2011. 5. Bullo, Plenary Speaker: 11th SIAM Conference on Control & Its Applications, Baltimore, MD, USA, Jul 2011 13. Bullo, Hugo Schuck Best Paper Award, American Automatic Control Council, 2011
14. Bullo, Plenary Speaker: 3rd IEEE Multi-Conference in Systems and Control, Saint Petersburg, Russia, Jul 2009 8. Bullo, Visiting Professor, University of Cagliari, Jul 2010
15. Bullo, Best Student Paper Award, ACC 2010 10. Bullo, IEEE Fellow, Class of 2010 11. Bullo, Article selection for inclusion in SIGEST section of SIAM Review, Mar 2009 12. Bullo, Outstanding Paper Award, IEEE Control Systems Magazine, 2008
16. Michael, Winner, Best Student Paper Award, Intl. Sym. on Distributed Auton. Syst., Lausanne, Switzerland, Nov. 2010.
17. Michael, Finalist, Best Paper Award, Intl. Conf. on Robot. and Autom., Shanghai, China, May 2011.
18. Michael, Finalist, Best Paper Award, Intl. Conf. on Robot. and Autom., Shanghai, China, May 2011. Second nomination.
19. Michael, Finalist, Best Paper Award, Conf. on Autom. Sci. and Eng., Trieste, Italy, Aug. 2011.
20. Rus, Best paper finalist, ICRA 2011
21. Rus, Best paper finalist, RSS 2010 19. Rus, Singapore Research Professor of Autonomous Systems Chair

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Joey Durham	0.07	
John Simpson	0.70	
Shaoshuai Mou	1.00	
David Stein	0.50	
Ryan Schoen	0.50	
Humberto Gonzalez	0.50	
Nora Ayanian	0.19	
Jungwon Seo	0.50	
Berkay Deniz Ilhan	1.00	
Jonathan Fink	0.18	
Ryan David Kennedy	0.08	
Daniel Mellinger	0.11	
Mahmut Selman Sakar	0.17	
Michael Conrad Zargham	0.75	
Matthaas Faessler	0.16	
Dimitra Panagou	0.33	
Ethan Stump	0.21	
Shaojie Shen	0.24	
Ji Liu	1.00	
Anahita Mirtabatabaei	1.00	
Florian Dorfler	1.00	
Seungkook Yun	1.00	
Lauren White	1.00	
Michael Conrad Zargham	0.72	
FTE Equivalent:	**12.91**	
Total Number:	**24**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Vinutha Kallem	0.22
Qimi Jiang	0.50
Ruggero Carli	0.50
Mac Schwager	1.00
Hoam Chung	1.00
David Shim	1.00
Jason C. Derennick	0.18
Ethan Stump	0.21
Edward Steager	0.83
Haldun Komsuoglu	0.20
FTE Equivalent:	**5.64**
Total Number:	**10**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Paulo Arratia	0.08	
Vijay Kumar	0.12	
Francesco Bullo	0.05	No
Ali Jadbabaie	0.08	
Daniel Koditschek	0.07	
Nathan Michael	0.15	
A. Stephen Morse	0.05	Yes
George Pappas	0.04	
Daniela Rus	0.10	
Shanker Sastry	0.03	Yes
David Skelly	0.08	
Max Mintz	0.04	
Maxim Likhachev	0.16	
FTE Equivalent:	**1.05**	
Total Number:	**13**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Michael Shomin	0.22	Mechanical Engineering
Christine Kappeyne	0.24	
Ceridwen S. Magee	0.24	
FTE Equivalent:	**0.70**	
Total Number:	**3**	

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: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 3.00

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:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 3.00

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	
Michael Shomin	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Stephen L. Smith	
Shaunak Bopardikar	
Karl J. Obermeyer	
Joey Durham	
Nora Anyanian	
Ethan Stump	
Spring Berman	
Seungkook Yun	
Carrick Detweiler	
Total Number:	**9**

Names of other research staff

NAME	PERCENT_SUPPORTED
Rebecca Stein	0.02
James F. Keller	0.01
Aleksandr Kushleyev	0.12
FTE Equivalent:	**0.15**
Total Number:	**3**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Our work over the past five years on the SWARMS project has included control theory, robotics, systems engineering and biology addressing swarming behaviors in nature and applications of biologically-inspired models of swarm behaviors to large networked groups of autonomous vehicles. The key objective was to draw inspiration from biological paradigms, to create a mathematical basis for modeling, analysis, and synthesis of swarming systems, which would be applicable to cooperative control tasks of all types, including the control of formations, the management of sensor networks, and the dynamics of achieving a consensus in a rapidly changing environment. In particular, it is critical to design algorithms that lend themselves to implementation in realistic swarm systems and that will scale well with the number of vehicles and devices present in the swarm. Accordingly, the Swarms project focused on four main research thrusts: modeling of group-behaviors in biology, analysis of group behaviors, synthesis of novel controllers for networked groups of vehicles, and experimental demonstrations and validation. Multiple papers have been published on the topic and reflect the tremendous progress we have made over the last few years. They also provided insights into different aspects of architecture design, controller synthesis, and communication protocols that will make autonomous groups of networked robots a reality.

Experimental study and modeling of group behaviors

Berman, Lindsey, Kumar and Pratt studied the cooperative behavior of ants engaged in collective transport tasks involving the retrieval of a prey to the nest. Ants are able to act independently with very little apparent coordination and yet accomplish the complex tasks of cooperative manipulation and transportation that an individual cannot accomplish on his/her own. They further investigated the application of models derived from ant behaviors to cooperative manipulation by robotic systems. In addition, Skelly's biological research has turned increasingly to understanding causes for reproductive deformities within amphibians living in suburban environments.

At a smaller scale, Kumar and Pappas have studied behavior of bacteria. One of the great challenges in microscale science and engineering is the independent manipulation of cells and man-made objects on the micron scale. Motile microorganisms are integrated with engineered systems to construct microbiorobots (MBRs). MBRs are negative photosensitive epoxy (SU8) microfabricated structures with typical feature sizes ranging from 1-100 μm coated with a monolayer of swarmer cells of the bacterium Serratia marcescens. The adherent cells naturally coordinate to propel the microstructures in fluidic environments. In this study, ultraviolet light is used to control rotational motion and direct current electric fields are used to control the two-dimensional movement of MBRs. They are steered in a fully automated fashion using computer-controlled visual servoing, used to transport and manipulate micron-sized objects, and employed as cell-based biosensors. We also developed an experimentally validated mathematical model for the MBRs. This model allows us to use self actuation and electrokinetic actuation to steer the MBR to any position and orientation.

Rus has developed a method for modeling animal interaction with the environment and interaction among multiple agents using data from smart collars. Data collected from cattle is used to identify the parameters of the model by least squares fitting. Techniques from Artificial Intelligence are used to synthesize a herd model with a realistically rich taxonomy of behaviors. Kumar and Pappas (in collaboration with H. Rubin) have been engaged in modeling bacterial colonies and their response to external stimulii. Models range from stochastic models of individual cells to deterministic models of ensembles of cells. Most recently, continuous-time Markov chain models have been developed to model the switching between different behaviors for Lactose induction in E.coli. This work is leading to the modeling and control of the motile behavior of fagellated bacteria and bacterial microactuation. Pappas has also developed a novel identification technique based on convex optimization for genetic regulatory networks based on genetic perturbation data.

Kumar (in collaboration with S. Pratt) has worked on hierarchical models at the population level, the group level and the individual level for ant colonies to allow design and analysis of behaviors at different levels of granularity. Skelly in collaboration with other members of the MURI team has been developing a database of collective behaviors that have both biological significance and tactical importance for DoD applications. Skelly and Rus have developed new ideas about biologically inspired modes of construction. In addition, Skelly's biological research has turned increasingly to understanding causes for reproductive deformities within amphibians living in suburban environments.

Pappas and coworkers employed convex optimization to identify the gene interaction topology from steady-state measurements of the mRNA concentrations of genes in bio-molecular networks. This problem is very important, not only in promoting biological knowledge, but also in dug discovery, where a systems wide understanding of the network is necessary. The novelty of our approach was a relaxation of the non-convex sparsity constraint (required if we want to identify a minimal set of connections) by an iterative solution of convex approximations of the problem. We were also able to incorporate prior biological knowledge, as well as noise in the data. Our approach was shown to perform particularly well on synthetic data as well as on data for the SOS pathway in E.coli.

Kumar and Pappas have developed stochastic models for bacterial swarms swimming in microchannels and used these models to develop approaches controlling swarms using chemotaxis and phototaxis.

Dynamic Vehicle Routing for Robotic Systems

Bullo et al discuss swarming of multiple autonomous vehicles focusing on the planning of optimal routes for multiple vehicles performing different spatially distributed tasks. The paper reviews the rich area of dynamic vehicle routing and provides a framework derived from queuing theory and combinatorial optimization. They establish fundamental limits on the achievable performance in the setting where the tasks are dynamically generated by exogenous processes.

The work on dynamic vehicle routing was completed by the graduation of PhD students Stephen L. Smith and Shaunak D. Bopardikar and the publication of the survey article in the Proceedings of the IEEE. For dynamic vehicle routing, our main contributions are the identification of (1) a novel tractable problem formulation, (2) problem structures (intrinsic regimes in parameter space, phase transitions, etc), (3) fundamental limitations on the achievable performance, and (4) efficient algorithms with guaranteed performance within a constant factor of the optimum. In the context of dynamic vehicle routing, we organized and delivered workshops at the 2010 ACC and the 2011 RSS conferences.

In the work of PhD student Joey Durham, we have proposed distributed algorithms to automatically deploy a group of mobile robotic agents to partition and provide coverage of a non-convex environment represented by a graph. Our graph coverage algorithm requires only short-range, unreliable pairwise ``gossip'' communication between the agents. The algorithm has two parts: a motion protocol to ensure the robots communicate with their neighbors, and a pairwise partitioning rule to update territory when two robots meet.

Deterministic Gossiping

Gossip algorithms are distributed, asynchronous algorithms for information exchange and computation in a network of nodes, where the nodes can be autonomous vehicles in a group. Liu, Mou, Morse, Anderson and Yu have developed a deterministic gossip protocol that is guaranteed to always generate a repetitively complete gossip sequence. The design of such provably correct deterministic protocols with exponentially convergent protocols has significant implications for the design of distributed control and estimation algorithms for groups of vehicles, each of which must derive estimates and make decisions independently while ensuring consensus at the group level.

Morse has also developed deadlock free, efficient solutions to the distributed averaging problem. Provided a complete solution to the acyclic formation control problem which exhibits “global stability” Provided a complete convergence proof for the adaptive version of the range only station keeping problem. Graph Theoretic Connectivity Control of Mobile Robot Networks Zavlanos, Egerstedt, and Pappas developed a mathematical framework for analyzing groups of vehicles connected by a communication network incorporating models of communication based on proximity. Their framework relies on a graph-theoretic definition of connectivity and the analysis, which leverages tools from algebraic graph theory and hybrid systems theory, points to approaches to controlling the network topology. Specifically, they formulate control laws for individual vehicles that guarantee maintenance of the network, accomplish tasks requiring rendezvous, and swarm in group formations.

Pappas et al also established a theoretical framework for controlling graph connectivity in mobile robot networks. We discuss proximity-based communication models composed of disk-based or uniformly-fading-signal-strength communication links. A graph theoretic definition of connectivity is provided, as well as an equivalent definition based on algebraic graph theory, which employs the adjacency and Laplacian matrices of the graph and their spectral properties. Based on these results, we discuss centralized and distributed algorithms to maintain, increase, and control connectivity in mobile robot networks. The various approaches discussed in this paper range from convex optimization and subgradient descent algorithms, for the maximization of the algebraic connectivity of the network, to potential fields and hybrid systems that maintain communication links or control the network topology in a least restrictive manner. Common to these approaches is the use of mobility to control the topology of the underlying communication network. We discuss applications of connectivity control to multi-robot rendezvous, flocking and formation control, where so far, network connectivity has been considered an assumption.

Decentralized Control for the Deployment of Robotic Camera Networks Schwager, Julian, Angermann, and Rus developed decentralized control policies for a group of aerial robots monitoring a specified area with cameras in a surveillance application. The cost function is derived from a model of a downward facing camera and is designed to maximize the number of pixels per unit area across the group. Each robot follows a gradient control law that ensures the group coverage is maximized and has guarantees on convergence and stability. Results are presented in simulation as well as in experimentation with a testbed of multiple quad rotor robots (autonomous helicopters with four rotors).

Rus et al have also developed a distributed control algorithm to command a group of robots to explore an unknown environment while providing adaptive sensor coverage of interesting areas within the environment. This algorithm has many applications in controlling teams of robots to perform tasks such as search and rescue missions, environmental monitoring, automatic surveillance of rooms, buildings, or towns, or simulating collaborative predatory behavior. This work extends our previous results on coverage developed as part of this project by removing restrictions on the weighting function, so that a much broader class of weighting functions can be provably approximated. Typically, the form of the weighting function isn't known a priori, and if this isn't accounted for directly then the learning algorithm could chatter between models or even become unstable. In simulations performed with a realistic weighting function, the original algorithm only explores in a local neighborhood of the robots resulting in a poor approximation of the weighting function. However, the new algorithm explores the entire space, successfully learning the weighting function with provable robustness. In the new algorithm, the robots partition the environment and perform a distributed exploration algorithm so that the unknown weighting function can be adequately approximated. They then switch, in an asynchronous and distributed fashion, to a coverage mode in which they deploy over the environment to achieve positions that are advantageous for sensing. The robots use an on-line learning mechanism to approximate the weighting function. Since we do not assume that the robots can perfectly approximate the weighting function, the parameter adaptation law for learning this function must be carefully constructed to be robust to function approximation errors. Without specifically designing for such robustness, it is known that many different types of instability can occur. There are many different techniques that have been proposed in the adaptive control literature to handle this kind of robustness, including using a dead-zone, the s-modification, and the e-modification. Specifically, we chose the dead zone technique and prove that the robots learn a function that has bounded difference from the true function, while converging to positions that are locally optimal for sensing with respect to the learned function. We have implemented the algorithm using a decentralized swarm of 6 iCreate robots with light sensors.

Cooperative and Non-cooperative Operations of Robotic Sensor Web Swarms Chung, Oh, Shim and Sastry review recent advances in wireless sensor networks and their evolution into robotic sensor webs which are heterogeneous collections of stationary and mobile sensors including robots. In particular, they discuss the cooperative control of networked unmanned aerial algorithms in tasks as pursuit and tracking and navigation in groups. Their paper includes novel ideas on system architecture, the design of model predictive controllers for multiple unmanned aerial vehicles and cooperative localization using multiple cameras on stationary or mobile nodes.

Technology trends point towards a fusion of wireless sensor networks with robotic swarms of mobile robots. Sastry et al have also studied the coordination and collaboration between networked robotic systems, featuring algorithms for cooperative operations such as unmanned aerial vehicles (UAVs) swarming. We have developed cooperative actions of groups of agents such as probabilistic pursuit-evasion game for search and rescue operations, protection of resources, and security applications. We have demonstrated a hierarchical system architecture which provides wide-range sensing capabilities to unmanned vehicles through spatially deployed wireless sensor networks, highlighting the potential collaboration between wireless sensor networks and unmanned vehicles. This work also includes a short review of our current research efforts in heterogeneous sensor networks, which is being evolved into mobile sensor networks with swarm mobility. In a very essential way, this represents the fusion of mobility of ensembles with the network embedded systems, the robotic sensor web.

Control of Ensembles of Aerial Robots

Michael and Kumar have addressed the problem of swarming with multiple unmanned aerial vehicles. They consider abstractions of groups where large collections are represented by a group of shape and position/orientation variables that have the structure of a low-dimensional manifold. They describe the swarming task on this low dimensional manifold and synthesize decentralized controllers that achieve the swarming task with proofs of convergence. They also show experimental and simulation results on a team of multiple quad rotors.

For smaller teams, Ayanian and Kumar have also worked towards implementing automatically synthesized controller for multirobot coordination on a group of quadrotors. In an environment with obstacles, we automatically synthesize controllers with guarantees on collision avoidance, maintenance of desired inter-robot constraints, and convergence. We do this by decomposing the workspace into obstacle-free cells, taking the Cartesian product of the robots' workspaces, and removing from the resulting space all coordinates which violate the set constraints (collision, communication, etc.). This space is composed of polytopes, on which we plan a discrete path to the goal. On each pair of polytopes until the goal polytope, we synthesize a navigation function which drives the system to the next polytope in the sequence. We have successfully implemented the controller on a single quadrotor, and plan to implement it on a group of quadrotors.

Constraint-aware Construction.

Rus et al have introduced a constraint-aware decentralized approach to construction with swarms of robots. We aim to create complex structures using heterogeneous sets of robots and parts. We abstract this process using tool delivery and assembly robots; delivery robots pick up parts and carry them from some part source into the construction site where assembly robots perform actuation tasks to add the parts to the structure. In our previous work we developed a set of adaptive algorithms for constructing truss structures given a target geometry, and demonstrated their feasibility experimentally. This research extends that work in two ways: first, by developing a novel partitioning algorithm that uses a detailed description of the target structure rather than a target geometry to distribute tasks among robots; second, by introducing a distributed algorithm for delivering parts in order to conform to physical constraints such as the stability of the structure and the ability of robots to reach areas in the structure. If we imagine the construction of a building, there is a strong natural set of constraints on the build order. These fall into two major categories: (1) physical constraints require supporting structures be set up first: one must lay a foundation before a wall, and the first floor before the second; (2) reachability constraints require that construction not block pending work: plumbing and electrical is installed between studs before drywall encloses the space, though neither rely on each other for support. Our research on constraint-aware construction addresses the problem of representing and conforming to both of these classes of constraints, and determining ways to maximize and automate parallelism. More specifically, we are given a team of robots, a blueprint of a desired structure, and a construction region Q. A subset of n of the robots are specialized as assembly robots and the rest are specialized as delivery robots. The blueprint describes the location, type, and physical requirements for stability of each object ("part") in the structure. The robots are given a local section of a blueprint, and have full knowledge of the progress of the construction of the target structure in the area surrounding them and their neighbors. Our new algorithm coordinates the construction of a given structure while maximizing parallelism across assembly robots and conforming to the physical constraints of the structure. The algorithm is guaranteed to construct the structure in an order that is feasible in that it does not prevent any sub-assembly from being completed. We have implemented the algorithms using an experimental setup of 2 assembly and 2 delivery robots. Our experimental setup used the robots to build multi-layer boxes to test physical constraints. Our experimental setup used the robots to build multi-layer boxes to test physical constraints, and rows of boards to test reachability constraints. The robots were built using the iCreate robot base and Crustcrawler arms with specialized grippers.

Optimal Periodic Patrolling Trajectories of UUVs Guarding a Channel

Given a number of patrollers, the channel patrol problem consists of determining the periodic trajectories that the patrollers must trace out so as to maximize the probability of detection of the intruder. Sastry's group has formulated this problem as an optimal control problem. We assume that the patrollers' sensors are imperfect and that their motions are subject to turn-rate constraints, and that the intruder travels straight down a channel with constant speed. Using discretization of time and space, we approximate the optimal control problem with a large-scale nonlinear programming problem which we solve to obtain an approximately stationary solution and a corresponding optimized trajectory for each patroller. In numerical tests, we obtain new insight - not easily obtained using geometric calculations - into efficient patrol trajectory design for up to two patrollers in a narrow channel where interaction between the patrollers is unavoidable due to their limited turn rate.

Analysis

Morse has addressed the analysis of formations, the management of sensor networks, and the dynamics of achieving a consensus in a rapidly changing environment. This approach is based upon the combined use of graph theory and the theory of dynamical systems which as an approach to swarming analysis/synthesis is very much in an early stage of development. By developing the tools to analyze and synthesize swarm behaviors, we are contributing to the growing knowledge base, which will be required to eectively deploy large groups of mobile autonomous agents and sensors.

Jadbabaie and Sastry addressed provably correct analysis of distributed optimization based control algorithms such as distributed Model Predictive Control (MPC). While there has been success stories in implementation for distributed Model Predictive Controllers, the key theoretical questions have been more or less open. To address this void a research plan has been devised, which uses ideas from Multi-Parametric Quadratic Programming and operator theory to develop a rigorous theory for distributed MPC. Specifically, the contributions in this area have been twofold: On one hand, recent results on infinite-horizon optimal control of spatially invariant systems have been extended to finite receding horizon control with input and state constraints. On the other hand, the produced results can be interpreted as an extension of the finite dimensional Multi Parametric Quadratic Programming-based analysis of receding horizon control to distributed, spatially invariant systems. It is assumed that the dynamics of each subsystem is uncoupled to the others, but the coupling appears through the infinite horizon cost function. Specifically, it was proven that for spatially invariant systems with constraints, optimal receding horizon controllers are piece-wise affine (represented as a convolution sum plus an offset). Moreover, the kernel of each convolution sum decays exponentially in the spatial domain mirroring the unconstrained infinite-horizon case. Furthermore, in another work, these results have been extended to the case were dynamics are heterogeneous and the underlying graph does not possess any group structure, but still the underlying centralized solution has an inherently decentralized architecture, meaning that the amount of information needed from the neighbors decays exponentially in a distance metric defined over the graph. Using the framework of dual Lyapunov techniques, we were able to derive density functions for navigation function based systems which provide a tool for controller composition due to their convexity properties.

Bullo has worked on models, algorithms and analysis tools with the objective to tackle complexity and achieve scalability in SWARMS networks. We obtained two sets of notable results. First, we designed task allocation algorithms with optimal asymptotic performance in environment with varying degrees of communication services. Second, we designed cooperative pursuit strategies for multi-pursuers/evader games in scenarios with limited sensing abilities and with motion constraints.

Pappas and co-workers derived fundamental results in connectivity control, and applied and extended to multi-robot tasks that require connectivity for completion. One such task is flocking of multiple agents. Velocity alignment critically depends on the connectivity specification. The great challenge in these tasks is the integration of continuous motion planning with control in the discrete space of networks and graphs. We were able to address this challenge by developing distributed hybrid controllers for the robots that jointly ensured connectivity as well as flocking behavior of the swarm.

On a similar vein, we employed graph theory and distributed optimization to address network design and identification issues for consensus and gene expression respectively. In the former case, we developed a distributed algorithm to obtain the edge weights of a Markov chain with fastest mixing rate. This algorithm relied on consensus of appropriately sampled instances of the Markov chain. Probabilistic guarantees were also provided. This result has many applications in scenarios where multiple observers need to create a probabilistic map of the traffic in an environment of interest. Fast mixing Markov chains are important for algorithm performance.

Synthesis

This thrust is closely linked to the modeling and analysis thrusts. Biological behaviors that are deemed to be of interest have been modeled and analyzed for performance. In this thrust, the problem of systematically design agent behaviors to realize the right behaviors is addressed. Thus models of herds, ants, and bacteria serve as inspiration for the synthesis of controllers for robots.

Specifically, vision-based control laws have been developed in the scope of the project, that use visual servoing by bearing, optical flow and time to collision measurements for 2D and 3D coordination. Another focus in the project is to synthesize distributed control laws that maintain and optimize connectivity of the network in a distributed fashion. As recent results suggested that the behavior of the vehicle swarm is directly related to a quanti¿able measure of connectivity of the underlying proximity graph, a distributed protocol has been developed which optimizes the connectivity of the multiagent system by implementing a super-gradient algorithm that tries to locally optimize the second smallest eigenvalues of the state dependent graph Laplacian.

In addition, Jadbabaie and Koditschek have developed a formalism for construction of decentralized navigation functions, and controllers that that minimize this function whose minimum is the desired configuration.

We have derived (weak) Input-to-State stability properties of navigation function based systems, which will allow us to formally study the interconnection stability characteristics of multiple agents and use the input-to-state stability property as a synthesis tool.

The synthesis of controllers for a swarm of robots has been addressed, to generate a desired two-dimensional geometric pattern specified by some simple closed planar curve, considering local interactions for collision avoidance and maintaining specified relative distance constraints. The controllers are decentralized in the sense that the robots do not exchange or sense each other’s state information. However, we assume that the robots have range sensors allowing them to obtain information about distances to neighbors within a known range. We establish stability and convergence properties of the controllers.

Pappas has worked on distributed control of multiagent systems with applications are related to assignment problems as well as control of connectivity of mobile networks. The proposed approaches extend from gradient flows on appropriately defined potential fields to hybrid dynamical systems. Notions from algebraic graph theory were also used and provided significant modeling tools.

Rus and co-workers have generated a number of new results, both theoretical and experimental, in deploying groups of robots using decentralized controllers. We developed a new theory under which several previously separate notions of multi-robot deployment were unified as different instances of distributed optimization of a particular cost function. Specifically, we showed that geometric robot deployment methods based on Voronoi decompositions, probabilistic methods based on maximizing detection likelihood or minimizing measurement variance, and artificial potential field based methods in which robots push away from each other by following the negative gradient of potential fields can all be derived as distributed gradient descent on the same cost function. The cost function has three main components that can be specialized to produce these different deployment methods, as well as many other kinds of multi-robot deployment schemes. This unified approach highlights the commonalities of these methods, each of which was developed separately in the literature using rather different models of the underlying problem.

The unified cost function provokes questions about the limits of general optimization based multi-robot deployment. For example, we proved that there is an inherent connection between the convexity of a multi-robot cost function and the multi-robot phenomenon of consensus (in which all robots meet at a common point, also known as rendezvous). Specifically, we proved that if we desire a group of robots to do some task that is not consensus (i.e. that can not be accomplished by all robots driving to the same point), the underlying cost function for the task must be nonconvex. This is important because nonconvex cost functions are potentially more difficult to optimize than convex ones, especially in a multi-robot context where the optimization must be distributed over a, ad hoc robot network. This work was presented at the International Symposium on Robotics Research (ISRR) in August, 2009, after which it was selected as one of the best papers of the conference and was submitted to a special issue of the International Journal of Robotics Research (IJRR) in January, 2010.

This new multi-robot deployment theory led to several algorithmic and experimental advances. For example, we developed decentralized controllers based on this theory to enable distributed construction, in which a team of robots constructs a structure in a distributed way based on high level plans. The distributed construction algorithm was presented at the International Symposium on Robotics Research (ISRR) in August, 2009. We also developed decentralized controllers to deploy underwater sensor nodes in an acoustic underwater sensor network. The nodes use a distributed gradient optimization scheme to move themselves up and down along tethers anchored to the sea floor in order to best measure the ocean around them. The controller was successfully tested experimentally on a network of underwater sensor nodes. This work was accepted for presentation at the ACM Conference on Networking Sensors and Systems (SenSys) in November of 2010. We also used a distributed gradient method to design controllers for aerial vehicles to act as communication relays for ground vehicles in an ad hoc network. The aerial vehicles position themselves to optimize a measure of the signal quality in the network using a realistic model of the signal to interference ratio. The controller was implemented experimentally on a group of flying quadrotor robots, and was presented at the International Conference on Robotics and Automation (ICRA) in May of 2010. Finally, we also developed an algorithm for positioning robots for distributed surveillance with on-board cameras to optimize a metric related to maximize the amount of information captured in the environment The algorithm works with heterogeneous groups of robot-born cameras in which the cameras may have different optical properties, and the robots may have different modes of mobility (e.g. some cameras may be mounted in a fixed position but able to swivel in place, while others may be fixed to flying robots with a full six degrees of freedom). The algorithm was successfully implemented a group of five flying quadrotor robots over an ad hoc network operating outdoors in a fully autonomous fashion. Repeated experiments were carried out with the five quadrotors to prove robustness under realistic operating conditions. The algorithm and experiments were submitted to a special issue of the Proceedings of the IEEE (the flagship journal of the IEEE), in May 2010.

Sastry and co-workers have developed methods using Outer Approximations as an External Active Set Strategy. Outer approximations are a well known technique for solving semi-infinite optimization problems. We show that a straightforward adaptation of this technique results in a new, external, active-set strategy that can easily be added to existing software packages for solving nonlinear programming problems with a large number of inequality constraints. Our external active-set strategy is very easy to implement, and, as our numerical results show, it is particularly effective when applied to discretized semi-infinite optimization or state-constrained optimal control problems. Its effects can be spectacular, with reductions in computing time that become progressively more pronounced as the number of inequalities is increased.

Further his group has derived results on the optimal detection of an underwater intruder. Given a number of patrollers that are required to detect an intruder in a channel, the channel patrol problem consists of determining the periodic trajectories that the patrollers must trace out so as to maximized the probability of detection of the intruder. We formulate this problem as an optimal control problem. We assume that the patrollers' sensors are imperfect and that their motions are subject to turn-rate constraints, and that the intruder travels straight down a channel with constant speed. Using discretization of time and space, we approximate the optimal control problem with a large-scale nonlinear programming problem which we solve to obtain an approximately stationary solution and a corresponding optimized trajectory for each patroller. In numerical tests for one, two, and three underwater patrollers, an underwater intruder, different trajectory constraints, and several intruder speeds, we obtain new insight — not easily obtained using simply geometric calculations — into efficient patrol trajectory design for multiple patrollers in a narrow channel where interaction between the patrollers is unavoidable due to their limited turn rate.

Their work has also led to advances in multi-agent cooperative and non-cooperative sensing and operation in dynamic environments.

Technology trends point towards a fusion of wireless sensor networks with robotic swarms of mobile robots. In this work, we discuss the coordination and collaboration between networked robotic systems, featuring algorithms for cooperative operations such as UAV swarming. We have developed cooperative actions of groups of agents such as probabilistic pursuit evasion game for search and rescue operations, protection of resources, and security applications. We have demonstrated a hierarchical system architecture which provides wide-range sensing capabilities to unmanned vehicles through spatially deployed wireless sensor networks, highlighting the potential collaboration between wireless sensor networks and unmanned vehicles. This work also includes a survey of our current research efforts in heterogeneous sensor networks, which is being evolved into mobile sensor networks with swarm mobility. In a very essential way, this represents the fusion of mobility of ensembles with network embedded systems.
Kumar and his students have develop methods to maintain connectivity using a network of aerial and ground robots exploiting models of line-of-sight connectivity and models that capture fading and shadowing. In collaborations with ARL researchers they have developed new models and control algorithms that enable robots to concurrently solve the problems of routing packets

and control.

Kumar and Pappas have developed bacteria-powered micro-robots that swim through microchannels influenced by chemicals in the environment. These proof of concept prototypes point to microrobots that can sense the environment and deliver drugs. Kumar and Michael have developed a framework and robot controllers that enable a group of aerial robots to maintain a formation with partial state information while avoiding collisions. The central idea is to develop a low-dimensional abstraction of the large teams of robots, facilitating planning, command and control in a low-dimensional space, and to realize commands or plans in the abstract space by synthesizing controllers for individual robots that respect the specified abstraction. We derive the basic theory and present experimental and simulation results with a team of rotor crafts.

Technology Transfer