Tucker Balch

Curriculum Vitae

College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

(404) 894-2000
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http://www.cc.gatech.edu/~tucker

Research Interests

Design and control of *effective* multi-agent systems, including:

- observing, tracking and modeling the behavior of multi-agent systems,
- diversity in multi-agent systems,
- distributed sensing and communication in bandwidth-limited environments,
- behavior-based strategies for multi-robot cooperation, and
- reinforcement learning in multi-agent teams.

Education

Ph.D., C.S., **GEORGIA INSTITUTE OF TECHNOLOGY** 1998
Thesis: *Behavioral Diversity in Learning Multi-robot Systems*
Advisor: Professor Ronald C. Arkin. Minor: Electrical Engineering

M.S., C.S. **UNIVERSITY OF CALIFORNIA AT DAVIS** 1988
Advisor: Professor Nelson Max. Focus: Surface Modeling for Computer Graphics

B.S., C.S. **GEORGIA INSTITUTE OF TECHNOLOGY** 1984
Graduated with honor

Current Appointments

GEORGIA INSTITUTE OF TECHNOLOGY
Assistant Professor of Computing 2001-Present

CARNEGIE MELLON UNIVERSITY
Adjunct Research Scientist, Robotics 2001-Present

Professional Experience

CARNEGIE MELLON UNIVERSITY
Research Scientist and Associate Director of the MultiRobot Lab 1999-2001
Postdoctoral Fellow with Professor Manuela Veloso 1998-1999

GEORGIA INSTITUTE OF TECHNOLOGY 1992-1998
Graduate Research Assistant, Mobile Robot Laboratory

JET PROPULSION LABORATORY Summer, 1996
Member of the Technical Staff, Robotic Vehicles Group

UNITED STATES AIR FORCE 1988-1996
F-15 Pilot

LAWRENCE LIVERMORE NATIONAL LABORATORY 1984-1988
Computer Scientist

Honors	**Outstanding Graduate Research Assistant of the Year**	Computing, Georgia Tech, 1996
Academic	**NASA Award for Technical Innovation**	Jet Propulsion Laboratory, 1997
	First Place, AAAI Mobile Robot Competition	Find Life on Mars Event, 1997
	First Place, AAAI Mobile Robot Competition	Clean Up the Office Event, 1994
Military	**Top Gun Team**	128th Fighter Squadron, 1991, 1992
	Best Instrument Pilot	USAF Pilot Training, 1989
	Distinguished Graduate	USAF Pilot Training, 1989

Publications

Books

1. **Designing Robot Behavior,** Balch, T., MIT Press, under contract.
2. **Robot Teams: From Diversity to Polymorphism,** Balch, T. and Parker, L. (eds), AK Peters, 2001.
3. **RoboCup-2000: Robot Soccer World Cup IV,** Stone, P., Balch, T., Kraetzschmar, G. (eds), Springer-Verlag, 2001.

Journal special issue edited

4. **Special Issue on Heterogeneous Multi-Robot Systems,** *Autonomous Robots,* Balch, T. and Parker, L. (eds), vol 8, no 3, July, 2000.

Peer-reviewed journal and magazine articles

5. **Hierarchic Social Entropy: An Information Theoretic Measure of Robot Team Diversity,** Balch, T., *Autonomous Robots*, vol 8, no 3, July, 2000. (also to appear as a chapter in *Robot Teams: From Diversity to Polymorphism*, Balch, T. and Parker, L. (eds), 2001.)
6. **Behavior-Based Formation Control for Multiagent Robot Teams,** Balch, T. and Arkin, R.C., *IEEE Transactions on Robotics and Automation*, December, 1998.
7. **AuRA: Principles and Practice in Review,** Arkin, R.C. and Balch, T., *Journal of Experimental and Theoretical Artificial Intelligence*, 9(1997): 175-189.
8. **Communication in Reactive Multiagent Robotic Systems,** Balch, T. and Arkin, R.C., *Autonomous Robots* 1(1)(1995): 27-52.
9. **Io, Ganymede and Callisto: A Multiagent Robot Trash-Collecting Team,** Balch, T., Boone, G., Collins, T., Forbes, H. MacKenzie, D. and Santamaria, J., *AI Magazine*, 16(2): 39-53.
10. **Profile of a Winner: Georgia Tech,** Balch, T., *AI Magazine*, Fall, 1998, (a review of Georgia Tech's winning multirobot entry in the AAAI-97 Robot Competition).
11. **Fast Obstacle Detection via Triangulation of Light Spots,** Matthies, L., Balch, T. and Wilcox, B., *NASA Tech Briefs*, 21(3), p. 52. (summary of a longer paper that appeared in ICRA-96).

Invited journal and magazine articles

12. **Overview of RoboCup-99,** Coradeschi, S., Karlsson, L., Stone, P., Balch, T., Kraetzschmar, G. and Asada, M. *AI Magazine*, 21(3), Fall, 2000.

13. **The AAAI 1999 Mobile Robot Competitions and Exhibitions,** Meeden, L., Schultz, A., Balch, T., Bhargava, R., Haigh, K., Bohlen, M., Stein, C. and Miller, D. *AI Magazine*, 21(3), Fall, 2000.

14. **Guest Editorial,** Balch, T. and Parker, L. *Autonomous Robots* Special Issue on Heterogeneous Multi-Robot Systems, 8(3), 2000.

15. **The CMU MultiRobot Lab,** Balch, T. *Robotics and Machine Perception*, 9(1), March, 2000.

16. **The AAAI-98 Mobile Robot Exhibition,** Haigh, K., Balch, T., *AI Magazine*, Spring, 2000.

17. **On the Directional Correlation of Axial Rotation in Inverted Felines and Planetary Spin,** Donahoo, M., Boone, G., Balch, T., *Journal of Irreproducible Results*, 44(5), January, 2000. (scientific humor).

18. **Grid-Based Navigation for Mobile Robots,** Balch, T., *The Robotics Practitioner*, 2(1), 1996.

Book chapters

19. **Taxonomies of Multi-Robot Task and Reward,** Balch, T., in *Robot Teams: From Diversity to Polymorphism*, Balch, T. and Parker, L. (eds), AK Peters, 2001.

20. **CMU Hammerheads,** (a description of our robot team entry in RoboCup-2000), Emery, R., Stroupe, A., Shern, R., Sikorski, K. and Balch, T., in *RoboCup-2000: Robot Soccer World Cup VI*, Stone, P., Balch, T. and Kraetzschmar, G. (eds), Springer-Verlag, 2000.

21. **Intelligent Robots,** Balch, T., *World Book 2001 Science Year,* World Book Encyclopedia, 2001 (to appear).

22. **Introduction and Overview of RoboCup-99,** Veloso, M., Kitano, H., Pagello, E., Kraetzschmar, G., Stone, P., Balch, T., Asada, M., Coradeschi, S., Karlsson, L. and Fujita, M. *RoboCup-99: Robot Soccer World Cup III*, Veloso, Pagello, Kitano (eds), Springer-Verlag, 2000.

23. **Cooperative Multiagent Robotic Systems,** Arkin, R.C. and Balch, T., *AI-based Mobile Robots: Case Studies of Successful Robot Systems*, D. Kortenkamp, R.P. Bonasso, and R. Murphy (eds), MIT Press, 1998.

24. **Communication and Coordination in Reactive Robotic Teams,** Arkin, R.C. and Balch, T., in *Coordination Theory and Collaboration Technology*, Olsen, G. (ed), in press.

25. **Integrating RL and Behavior-Based Control for Soccer,** Balch, T., *RoboCup-97: Proc. of the First Robot World Cup Soccer Games and Conferences*, Springer-Verlag, 1998. (also appears in IJCAI-97 Workshop proceedings).

26. **JavaSoccer,** Balch, T., *RoboCup-97: Proc. of the First Robot World Cup Soccer Games and Conferences*, Springer-Verlag, 1998.

Refereed conference papers

26. **Symmetry in Markov Decision Problems and Implications for Single and Multiagent Learning**, Zinkevich, M. and Balch, T., *Eighteenth International Conference on Machine Learning (ICML-2001).*

27. **Automatically Tracking and Analyzing the Behavior of Live Insect Colonies,** Balch, T., Khan, Z. and Veloso, M., *Autonomous Agents (Agents 2001)*, Montreal.

28. **Distributed Sensor Fusion for Object Position Estimation by Multi-Robot Systems,** Stroupe, A., Martin, M. and Balch, T., *IEEE International Conference on Robotics and Automation (ICRA-2001)*, Seoul, 2001. (also presented at 2000 International Symposium on Experimental Robotics. Honolulu, HI.)

29. **Behavior-Based Control of a Non-Holonomic Robot in Pushing Tasks,** Emery, R. and Balch, T., *IEEE International Conference on Robotics and Automation (ICRA-2001)*, Seoul, 2001.

    —nominated for ICRA Best Student Paper Award—

30. **Fast and Inexpensive Color Image Segmentation for Interactive Robots,** Bruce, J., Balch, T. and Veloso, M., *IROS-2000*, (also published as workshop paper in WIRE-2000).

31. **Social Potentials for Scalable Multirobot Formations,** Balch, T. and Hybinette, M., *IEEE International Conference on Robotics and Automation (ICRA-2000)*, San Francisco, 2000.

32. **Behavior-Based Coordination of Large-Scale Robot Formations,** Balch, T. and Hybinette, M., *International Conference on Multiagent Systems (ICMAS-2000)*, Boston, 2000.

33. **Vision-Servoed Localization and Behaviors for an Autonomous Quadruped Legged Robot,** Veloso, M., Winner, E., Lenser, S., Bruce, J., and Balch, T. *Artificial Intelligence Planning Systems (AIPS-2000).*

34. **Integrating Information, Planning, and Execution Monitoring Agents,** Veloso, M., Balch, T., and Lenser, S., *Autonomous Agents (Agents-2000)*, Barcelona, 2000.

35. **The Impact of Diversity on Performance in Robot Foraging,** Balch, T., *Autonomous Agents (Agents-99)*, Seattle, WA, May, 1999.

36. **Teaming Up: Georgia Tech's Multirobot Competition Teams,** Collins, T. and Balch, T., *Proc. of the 1997 AAAI National Conference on A.I. (AAAI-97)*, Providence, July 1997, 785-86.

37. **Fast Optical Hazard Detection for Planetary Rovers Using Multiple Spot Laser Triangulation,** Matthies, L., Balch, T. and Wilcox B., *IEEE International Conference on Robots and Automation (ICRA-97)*, Albuquerque, NM, April 1997.

38. **Design and Implementation of a Teleautonomous Hummer,** Bentivegna, D.C., Ali, K.S., Arkin, R.C., Balch, T., *Proc. SPIE Conference on Mobile Robots XII*, Pittsburgh, Oct 1997.

39. **Social Entropy: A New Metric for Learning Multirobot Teams,** Balch, T., *Proc. of the 10th International FLAIRS Conference (FLAIRS-97)*, Daytona, 1997.

40. **Lightweight Rovers for Mars Science Exploration and Sample Return,** Schenker, P., Sword, L., Ganino, A., Bickler, D., Hickey, G., Brown, D., Baumgartner, E., Matthies, L., Wilcox, B., Balch, T., Aghazarian, H. and M. S. Garrett, *Proc. Intelligent Robotics and Computer Vision XVI*, SPIE Proc. 3208, Pittsburgh, Oct. 14-17, 1997.

41. **Motor Schema-Based Formation Control for Multiagent Robot Teams,** Balch, T. and Arkin R.C., *International Conference on Multiagent Systems (ICMAS-95)*, San Francisco, April 1995.

42. **Avoiding the Past: a Simple but Effective Strategy for Reactive Navigation,** Balch, T. and Arkin R.C., *IEEE International Conference on Robots and Automation (ICRA-93)*, Atlanta, May 1993, 678-685.

43. **Communication of Behavioral State in Multi-Agent Retrieval Tasks,** Arkin, R.C., Balch, T. and Nitz, E., *IEEE International Conference on Robots and Automation (ICRA-93)*, Atlanta, May 1993.

Refereed workshop and symposium papers

44. **Model-based and Model-free Learning in Markovian and non-Markovian Domains**, Sikorski, K. and Balch, T., *Autonomous Agents (Agents 2001) Workshop on Learning Agents*, Montreal.

45. **Progress in RoboCup Soccer Research in 2000,** M. Asada, A. Birk, E. Pagello, M. Fujita, I. Noda, S. Tadokoro D. Duhaut, P. Stone, M. Veloso, T. Balch, H. Kitano, B. Thomas. *Internatial Symposium on Experimental Robotics*, Honolulu, Dec, 2000.

46. **Hierarchic Social Entropy and Behavioral Difference: New Measures of Robot Group Diversity,** Balch, T., *NIST Workshop on Metrics for Intelligent Systems* , Gaithersburg, July, 2000.

47. **Behavioral Diversity as Multiagent Cooperation,** Balch, T., *SPIE '99 Workshop on Multiagent Systems*, Boston, 1999.

48. **Reward and Diversity in Multirobot Foraging,** Balch, T., *IJCAI-99 Workshop on Agents Learning About and with Other Agents*, Stockholm, 1999.

49. **JavaBots,** Balch, T., *Video Proc. of the 1998 AAAI Mobile Robot Exhibition*, Madison WI, July 1998.

50. **Integrating Robotics Research with JavaBots,** Balch, T. and Ram, A., 1998. *Working Notes of the AAAI 1998 Spring Symposium*, Stanford.

51. **Robots Move** (position paper on robot simulation), Balch, T., 1998. *Working Notes of the AAAI 1998 Spring Symposium*, Stanford.

52. **Learning Roles: Behavioral Diversity in Robot Teams,** Balch, T., *Proc. of the 1997 AAAI Workshop on Multiagent Learning*, Providence RI, July 1997.

53. **Lessons Learned in the Implementation of a Multirobot Trash-Collecting Team,** Balch, T., *Working Notes of the AAAI 1995 Spring Symposium*, Stanford, March 1995.

54. **Dynamic Scheduling for Mobile Robots,** Balch, T., Forbes, H., and Schwan, K., *Proc. 6th EUROMICRO Workshop on Real-time Systems*, Västerås, Sweden, June 1994.

55. **Making a Clean Sweep: Behavior-Based Vacuuming,** MacKenzie, D. and Balch, T., *Working Notes of 1993 AAAI Fall Symposium: Instantiating Real-world Agents*, Raleigh, NC, March 1993.

56. **Buzz: An Instantiation of a Schema-Based Reactive Robotic System,** Arkin, R.C., Balch, T., Collins, T., Henshaw, A., MacKenzie, D., Nitz, E., Rodriguez, R., and Ward, K., *Proc. International Conference on Intelligent Autonomous Systems: IAS-3*, Pittsburgh, Feb. 1993, 418-427.

Invited presentations

56. **CMU Robotics Institute Seminar,** *Educating with and about Robots,* (organizer and speaker), Pittsburgh, December, 2000.

57. **Workshop on Performance Metrics for Intelligent Systems,** *Performance/N is the Wrong Metric for Multirobot Teams,* Gaithersburg, August, 2000.

58. **CMU Seminar on Robotics Education,** *TeamBots Junior,* Pittsburgh, June, 2000.

59. **ICRA-2000 Workshop on Sensor-based Navigation,** *The Case for Randomized Search,* San Francisco, April, 2000.

60. **Westinghouse High School Initiative,** invited talk on intelligent machines and robotics, Pittsburgh, January, 2000.

61. **Smithsonian Institution,** invited demonstration of soccer robots, December, 2000.

62. **CMU VASC Seminar,** *Control of large-scale robot teams*, Pittsburgh, 1999.

63. **AAAI-98 Robot Competition Workshop,** invited panelist, Madison, WI, 1998.

64. **Royal Institute of Technology,** *Multirobot Foraging: Cooperation, Communication and Learning*, Stockholm, Sweden, 1998.

65. **CMU Reinforcement Learning Seminar,** Behavioral diversity in learning robot teams, Pittsburgh, 1997.

66. **AAAI-94 Robot Competition Forum,** The Georgia Tech robot competition team, Seattle, WA 1994.

Media Coverage

- **New Scientist Magazine,** article in preparation, Yudhijit Bhattacharjee.
- **National Public Radio,** story in preparation, Lee Gutkind.
- **New Scientist Magazine,** "Follow that Ant," Catherine Zandonella, June, 2001.
- **Baltimore Sun,** "A Smarter Breed of Robots," Michael Stroh, June 29, 2001.
- **Computerworld,** "Ant Colony IT," Gary H. Anthes, June, 2001.
- **Public Broadcasting System**, "Beyond Human," Thomas Lucas Productions, May, 2001.
- **www.space.com,** "Space ANTS: Futuristic Probes to Cruise Asteroid Belt," Andrew Bridges, December, 2000.
- **The Chronicle of Higher Education,** "Carnegie Mellon Works to Make Computers Invisible and Pervasive," Florence Olsen, October 12, 2000.
- **The Associated Press**, "Computers, Robots Set to Play Soccer" August, 2000.
- **The Pittsburgh Post-Gazette,** "We, robots: CMU's 2000 RoboCup Entry Sports Members Whose Minds Mesh," Byron Spice, Science Editor August 14, 2000.
- **The Associated Press,** "Rescue Robots: Competition Tests Robot's Life-Saving Abilities," Connie Mabin, July 31, 2000.
- **The Pittsburgh Tribune-Review**, "Sci-fi robots slowly becoming reality," Mark Houser, May 2, 2000.
- **Computerworld**, "The Robots are Coming!" Gary Anthes, May 22, 2000.
- **Scientific American Frontiers (PBS),** "Natural Born Robots," November 2, 1999.

Students

Current

Ravi Balasubramanian, Ph.D. student, Robotics, CMU.
Rosemary Emery, Ph.D. student, Robotics, CMU.
Zia Khan, Junior, Biology, CMU.
Rande Shern, M.S. student, Computer Aided Learning and Discovery (CALD), CMU.
Kevin Sikorski, M.S. student, Robotics, CMU.
Steve Stancliff, Ph.D. student, Robotics, CMU.
Ashley Stroupe, Ph.D. student, Robotics, CMU.

Research & Thesis Committees

Brett Browning, Ph.D. 2001, University of Queensland, Australia.
Curt Bererton, Ph.D. (expected 2002), Robotics, CMU.
Vince Cicirello, Ph.D. (expected 2003), Robotics, CMU.
Poj Tangamchit, Ph.D. (expected 2002), ECE, CMU.

Former Students

James Bruce, B.S., C.S., 2000, CMU. Winner of the CRA Honorable Mention for Outstanding C.S. Senior. Now CMU C.S. Ph.D. student.
Mikhail Osterfeld, M.S. ECE 2000, CMU. Now US Army Officer.
John Sweeney, B.S. C.S. 2000, CMU. University of Mass., Amherst Ph.D. student.

Service

Academic	**Chair, CMU Robotics Graduate Student Admissions Committee**	2001
	Member, CMU Robotics Grad Student Admissions Committee	2000
	Organizer, CMU Workshop on Robotics Education	2000
Editor	**Autonomous Robots**, Special Issue on Heterogeneous Multirobot Systems	2000
	Video Proc. of the AAAI-98 Robot Exhibition	1998
Conference Organization	**Chair, AAAI Mobile Robot Competition and Exhibition**	2001
	Associate Chair for Robot Events, RoboCup-2001	2001
	Co-Chair, AAAI Mobile Robot Competition and Exhibition	1998,1999,2000
	Chair and Organizer, Workshop on Interactive Robotics and Entertainment	2000
	Co-Chair, RoboCup Workshop	2000
	Chair, RoboCup Small Robot League	1999,2000
	Co-Chair, RoboCup Small Robot League	1998
Program Committees	**International Conference on Robotics and Automation (ICRA)**	2000,2001
	Autonomous Agents	2000,2001
	RoboCup Workshop	1999,2000,2001
	National Conference on AI (AAAI)	1999,2000
	International Conference on Machine Learning (IMCL)	2000
	Distributed Autonomous Robot Systems (DARS)	2000
	Workshop on Collective Robotics	1998
Reviewer for	**Autonomous Robots**	
	IEEE Transactions on Robotics and Automation	
	IEEE Transactions on Systems, Man, and Cybernetics	
	Robotics and Autonomous Systems	
	SIGGRAPH	
	NSF	
Society Memberships	**Association for Computing Machinery**	
	Institute of Electrical and Electronics Engineers	
	IEEE Computer Society	
	IEEE Robotics and Automation Society	
	American Association for Artificial Intelligence	
	Air Force Association	
	National Guard Association of the United States (NAGAUS)	
	National Guard Association of Georgia	

Teaching

Graduate

16-869 (CMU) Autonomous Multirobot Systems Fall 1999, Fall 2000
Designed and taught new graduate course on multirobot systems.

CS 7100 (GT) Intro. to Grad. Studies, guest lectures, designed projects Fall 1997
CS 7323 (GT) Autonomous Robotics, guest lectures Winter 1995, Winter 1996

Undergraduate

EE 4813 (GT) Sensor-based Robotics, guest lectures, designed assignments Spring 1997
CS 1501 (GT) Introduction to Computing, guest lectures Spring 1997
CS 3361 (GT) Introduction to AI, guest lectures Winter 1995

Funding

Current

Principal Investigator, DARPA, *Reconnaissance Surveillance and Targeting Unmanned Ground Combat Vehicle*, joint project with Battelle, total project funding: $500K.

Co-Investigator, DARPA Contract F30602-98-2-0135, *Teams of Autonomous, Cooperative, and Adaptive Agents*, with Manuela Veloso, total project funding: $1.2M.

Co-Investigator, DARPA Contract DABT 63-99-1-0013, *Learning Structure, Reusability, and Real-time Modeling in Teams of Autonomous Robots*, with Manuela Veloso, total project funding: $1.5M.

Principal Investigator, Kitano Symbiotic and RoboCup Contract SIM-001, *TeamBots as a RoboCup Junior Simulation Platform*, total project funding: $40K.

Principal Investigator, Northrop-Grumman Research Grant, *Robot Swarms*, total project funding: $50K.

Faculty Development Grant, CMU, *A Computer Vision-based Testbed for Observing and Modeling Insect Behavior*, total project funding: $7K.

Pending

Principal Investigator, National Science Foundation, *Automatic Observation and Modeling of Social Insect Behavior,* in collaboration with Deborah Gordon, Stanford University.

Recent Research

Observing and modeling the behavior of social insects CMU, Spring 2000-Present
Ours is the first laboratory to apply multi-agent systems research to the study of social insect behavior. My students Zia Khan and Rande Shern and I are pioneering this new domain for multi-agent systems research by contributing novel automated vision, tracking and modeling algorithms as well as documenting methods for keeping ants in the laboratory. Social insects provide a rich source of *traceable* social behavior, and by successfully modeling them we will contribute new multi-agent science and new biological science as well. This work will be published in *Autonomous Agents*. More information is available on the web at `http://www.cs.cmu.edu/~multirobotlab/biotracking`

Distributed sensing for multi-robot systems CMU, Spring 2000-Present
This research with student Ashley Stroupe enables multiple robots to "see" what any one of them senses, and to improve the confidence of an object's position when more than one robot sees it. We use a probabilistic approach whereby observations are represented as two-dimensional Gaussian distributions. The robots communicate these representations about objects they see, then fuse them using a method similar to Kalman-Bucy filters. This work has been presented at the *International Symposium on Experimental Robotics* and has been submitted to *ICRA-2001*.

Large scale multi-robot teams CMU, Fall 1999-Present
My students and I are building one of the largest fully autonomous multirobot systems ever — 15 robots in all. I lead a group of 5 faculty and students in the design, construction and programming of these robots. In our first year we have already competed successfully in RoboCup World Cup soccer; winning four games and reaching the mid-size league playoffs. The robot platform developed in this work is used for a number of research projects. This work has been submitted for publication to *ICRA-2001*. More information is available on the web at `http://www.cs.cmu.edu/~coral/minnow`

Learning and diversity in multirobot systems Georgia Tech and CMU, 1995-Present
This research focuses on discovering what causes agents to learn different behaviors while working as a team, and to develop metrics for evaluating this diversity. Our results indicate that robot teams diversify to varying degrees depending on the task and the type of reinforcement they receive. This work has been presented at *Autonomous Agents '99*. A Java-based online demonstration is available at `http://www.cc.gatech.edu/grads/b/Tucker.Balch/socbots`

TeamBots Java-based robot control Georgia Tech and CMU, 1996-Present
My students and I have developed a Java-based system for real-time multirobot control that runs on robot hardware or in a graphical simulation. It has been demonstrated on Nomad 150 robots and on Probotics' Cye robots. The software is available for download at `http://www.teambots.org`

Social potentials for scalable robot formations Georgia Tech and CMU, 1994-Present
In this work with Ron Arkin, we developed new robot behaviors for multirobot formation. Behaviors were implemented in simulation, on a team of Denning mobile robots and on DARPA 4-wheel drive vehicles. Two- and three-HUMMER formations were demonstrated in March 1996 at DARPA's UGV Demo II. Results have been published in *Transactions on Robotics and Automation*, and presented at *International Conference on Multiagent Systems*.

Robotic Planetary Rover Research NASA/Jet Propulsion Laboratory, Summer 1996
In this work with Larry Matthies and Brian Wilcox, we implemented a novel hazard detection sensor system using structured light. The system was fielded on LSR-1, a new prototype planetary rover and it may be incorporated on a future Mars rover. The work received a NASA award for technical innovation. It was published in *NASA Tech Briefs* and presented at the *IEEE International Conference on Robotics and Automation*.

References

Dr. Manuela Veloso, Associate Professor
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Dr. Ronald C. Arkin, Professor and Director, Mobile Robot Laboratory
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280
Phone: (404) 894-8209 E-mail: arkin@cc.gatech.edu

Dr. Hans Moravec, Principal Research Scientist
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