AFRL-SR-AR-TR-04-
0642

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
10/1/2004

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL RPT November 2000 – August 2004

4. TITLE AND SUBTITLE
COORDINATED CONTROL OF VEHICLE GROUPS

5. FUNDING NUMBERS
F49620-01-1-0382

6. AUTHOR(S)
Vijay Kumar and Naomi Ehrich Leonard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Pennsylvania,
Office of Research Services,
Rm. P-221, 3451 Walnut Street
Philadelphia, PA 19104

Princeton University
Office of Research & Project Admin.
Fourth Floor, New South Building
PO Box 36
Princeton, NJ 08544-0036

8. PERFORMING ORGANIZATION REPORT NUMBER
537415

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NA, 801 N. Randolph Street,
Room 732, Arlington, VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

This project focuses on cooperation in the context of coordinated control of distributed, autonomous agents and the collection and fusion of the sensor information that they retrieve. Central is the synthesis and analysis of high-performance, group-level properties from simple control laws at the individual agent level. There are three main objectives: (1) to develop a theoretical paradigm for formalizing the concepts of a group, a team, and control of groups, with specified tasks such as exploring, mapping, searching and transporting objects; (2) to develop new algorithms for the organization, reconfiguration and control of vehicles that will scale to different types of vehicles, larger numbers and different tasks; and (3) to develop practical tools that can be used to develop solutions to practical problems and as proofs-of-concept for testing and generating new prototypes. These practical tools include a new simulation environment and software for testing new controllers and estimators, and experimental test beds for validation of algorithms.

14. SUBJECT TERMS
coordinated control, controllers

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

COORDINATED CONTROL OF VEHICLE GROUPS

GRANT #F49620-01-1-0382

Vijay Kumar
Mechanical Engineering and Applied Mechanics
GRASP Laboratory
University of Pennsylvania

Naomi Ehrich Leonard
Department of Mechanical and Aerospace Engineering
Princeton University

Abstract

This project focuses on cooperation in the context of coordinated control of distributed, autonomous agents and the collection and fusion of the sensor information that they retrieve. Central is the synthesis and analysis of high-performance, group-level properties from simple control laws at the individual agent level. There are three main objectives: (1) to develop a theoretical paradigm for formalizing the concepts of a group, a team, and control of groups, with specified tasks such as exploring, mapping, searching and transporting objects; (2) to develop new algorithms for the organization, reconfiguration and control of vehicles that will scale to different types of vehicles, larger numbers and different tasks; and (3) to develop practical tools that can be used to develop solutions to practical problems and as proofs-of-concept for testing and generating new prototypes. These practical tools include a new simulation environment and software for testing new controllers and estimators, and experimental test beds for validation of algorithms.

1. Introduction

This project report reports on progress made since the inception in November 2001 through August 2004. The main accomplishments are the development of new formalisms, frameworks and algorithms for the coordination of agents, groups of agents, and groups of groups, and the mathematical techniques that are necessary to develop models for these systems. We have developed and demonstrated on experimental platforms novel algorithms for cooperative localization and formation control in manipulation and mapping tasks. The Penn-Princeton collaboration has allowed the groups to address complementary issues, while allowing synergistic interactions on overlapping research problem areas, as both primary vehicles of interest are buoyant with respect to the medium in which they operate and, as such, they are subject to a variety of unique effects due the interaction of their own configuration with their local environment. We have made significant progress on the development of the Penn blimp platform and Clodbuster autonomous ground vehicle fleet, and the Princeton underwater vehicle testbed. We have developed several key demonstrations that illustrate the application of our methodologies and algorithms to truly three-dimensional experimental platforms. In the next section we provide more details on our key accomplishments.

2. Accomplishments

2.1. Visual servoing

We (Penn) have developed vision-based control and estimation strategies for flight control of a quadrotor (four-rotor helicopter). Our experimental testbed is shown in Figure 1 [31]. The motivation is to provide short-range, highly mobile visual feedback for a ground-based vehicle.

We have developed novel back-stepping control algorithms to control such UAVs. The state estimation uses visual feedback, with a novel two camera arrangement in which a ground based camera spots the quadrotor, while an onboard camera also tracks the ground-based station. This provides for increased robustness in estimating both position and orientation of the aerial vehicle than would be provided by traditional stereo or monocular techniques. Even in the presence of large errors in camera calibration parameters or on image values, global convergence can be achieved in many special, but important cases. The proposed pose estimation algorithm and the control techniques have been implemented on a remote controlled, battery powered model helicopter.

2.2. Coordinated and cooperative control

At Princeton University, we (Leonard and co-workers) have investigated gradient climbing with communication restricted only to near neighbors [7], [8]. In this setting, we have been able to prove convergence results even when each vehicle carries only a single sensor to sample the environment. To account for each vehicle having only one sensor with which to sample the environment, we use the projection of the full gradient onto the direction of motion for each individual vehicle. This gives rise to a differential equation with discontinuous right-hand side. In order to avoid the (practical and theoretical) complications that arise as a consequence of these discontinuities, we consider a modification of the inter-vehicle forcing terms and represent the velocity of each vehicle by a magnitude and an angle (quasi-polar coordinates), resulting in a set of smooth differential equations [7].

In parallel with this effort and motivated by an interest in imposing a task on the vehicle (mobile sensor) network, we developed a methodology for formation control and gradient climbing based on virtual bodies and artificial potential [13], [5]. Our control strategy and Lyapunov-based stability proof provide for translation, rotation, expansion and contraction of a vehicle formation. These then form the basic elements for (sensor-based) missions; we focused on gradient climbing missions with group contraction and expansion driven by the sensed environment. We have further developed this work to consider the optimal configuration for minimization of the least square error in the gradient estimate. We have applied this work to an adaptive ocean sampling problem using a fleet of underwater gliders [6]. We successfully demonstrated our ability to coordinate the behavior of a formation of underwater gliders in the presence of significant operational constraints and environmental disturbances during an experiment in Monterey Bay, in August 2003 [19] (see http://www.princeton.edu/~dcsl/aosn).

In another effort, we derived an approach to obstacle avoidance for a group of unmanned vehicles moving in formation [4]. The goal of the group is to move through a partially unknown environment with obstacles and reach a destination while maintaining the formation. We address this problem for a class of dynamic unicycle robots. Using Input-to-State Stability we combine a general class of formation-keeping control schemes with a new dynamic window approach to obstacle avoidance in order to guarantee safety and stability of the formation as well as convergence to the goal position. An important part of the approach can be seen as a formation extension of the configuration-space obstacle concept.

We have also considered the problem of coordination of mechanical systems with unstable dynamics [12]. The control law is derived using the Method of Controlled Lagrangians together with potential shaping designed to couple the mechanical systems. The coupled system is Lagrangian with symmetry, and energy methods are used to prove stability and coordinated behavior. The class of mechanical systems we consider includes the planar inverted pendulum on a cart as well as the spherical inverted pendulum on a 2D cart. For these examples, the control law stabilizes each inverted pendulum and coordinates the relative motion of the carts.

Related to this work, we have derived control laws for coordinating rigid bodies in 3D. In particular, we have addressed the problem of aligning the orientations of rigid bodies that may be spinning or translating together [15], [16]. In these cases each individual in the group has rigid body dynamics which may or may not be stable.

Other recent accomplishments include coordination results for a group consisting of constant-speed particles with heading control only [17], [18]. In this case the individuals are modeled like nonholonomic vehicles (unicycles). The heading control provides a controlled system that resembles coupled oscillator models, and the development and analysis exploits this analogy. We study and prove stability of both polarized motions of the group (all with synchronized headings) as well as circular patterns (the "anti-synchronized" case).

2.3. Cooperative control and localization

We (Penn) proposed [27][30] a hierarchical modular framework which allows us to model vehicle formations as a dynamically reconfigurable network for accomplishing cooperative tasks. Our framework integrates vision based control, cooperative localization and decentralized leader-follower control. Vision based control is achieved by a single omni-directional sensor. Our cooperative localization allows fast distributed estimation of team pose in the presence of sensing uncertainty. Dynamic reconfiguration is achieved by hybrid stabilization of the formation to a desired configuration using a switched control system model and graph-based algorithms. We decouple the problem of cooperative task specification from the team-level role assignment and organization. Our formation control approach allows us to do dynamic obstacle avoidance using the virtual leader idea (see simulated scenario in Figure 2).

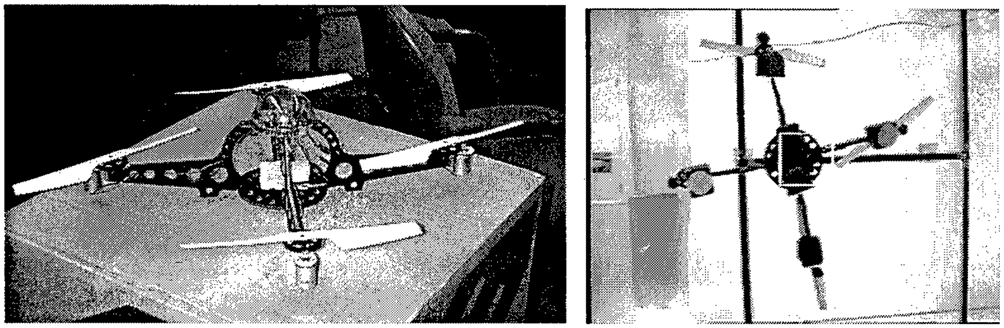

Figure 1: A four rotor helicopter (quadrotor) used in visual servoing experiments (left). A sample image obtained from a ground-based camera (right).

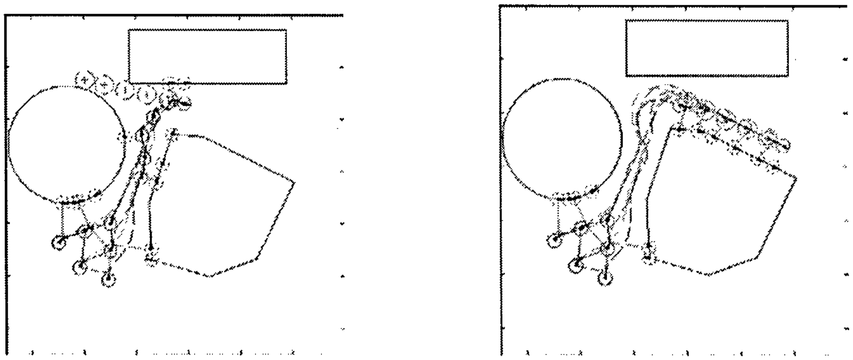

Figure 2: A six-vehicle formation achieving a straight line shape (magenta dashed circles) assignment while avoiding obstacles and following a specified leader. Virtual leaders (red dotted circles) are created at points on obstacles that are closest the physical vehicles allowing the vehicles to avoid obstacles.

We have applied the above framework to the problem of cooperative manipulation – ground based vehicles manipulating an object. The problem reduces to designing decentralized control policies for individual agents that satisfy the constraints of the manipulation task. We use geometric and dynamic models to synthesize decentralized controllers that allow individual agents to coordinate their movements while maintaining a condition that we call *object closure* [24] [28]. Object closure entails a set of conditions that essentially describe the trapping of a designated object and prevent it (under the worst case dynamics) from escaping.

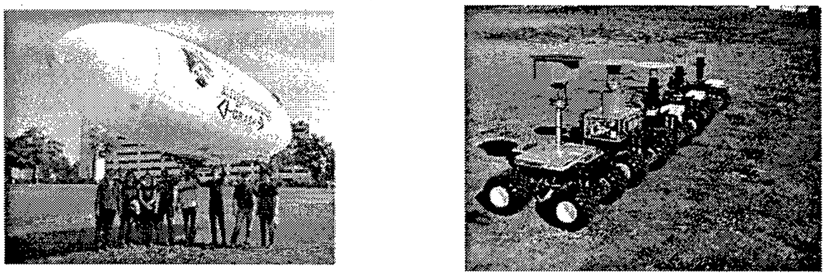

Figure 3: Penn 9 m. airship (left). Each agent uses a decentralized controller to coordinate its motions with respect to its neighbors to perform a cooperative manipulation task (right).

In 2004, at the University of Pennsylvania we further investigated cooperative localization and control of networked vehicle groups [37], [38]. We established a framework for active perception utilizing a graphical representation of sensory information obtained from heterogeneous sensors on vehicles [37]. Based on this model, we proposed necessary and sufficient conditions that establish when a group of vehicles with sensors can be completely localized in an unknown environment. We proved that these conditions for localization of multi-vehicle networks are compatible with the results for closed-chain kinematics of planar mechanical networks. We showed how localization of vehicle groups is equivalent to solving a system of nonlinear closure equations [38]. Experiments with multiple car-like mobile robots (see Figure 3, right frame) were conducted and showed how the topology of the network and underlying conditions affects the localization results.

In another effort, we have built a control scheme for vehicle groups with distributed sensors, which enables adapting of optimal multi-vehicle formations to reduce errors in localization [37], [39]. Motivated by the fact that sensors generally have a limited range and field of detection and their accuracy often varies with range, we found that depending on the information that needs to be acquired in a task, vehicles can be positioned appropriately and even optimally. Experimental measurements of range and bearing with omni-directional cameras and stereo cameras were investigated to build models for noisy sensory information. Based on these noise models, we presented a cooperative control framework and algorithms for actively adapting the formation of the vehicle group in order to optimize localization and information acquisition performance. This approach can be used for deployments of vehicle groups in both two and three dimensions and for different sorts of sensors with different noise characteristics.

2.4. The Princeton Experimental Test-Bed

We (Princeton) have developed a 3D multi-vehicle experimental test-bed that operates in a water tank. Our vehicles can be controlled in the tank. Advanced sensing is under development, and we have custom designed our own temperature sensors for the grouper vehicles so that we can use the group as a mobile sensor network to climb temperature gradients (e.g., find hot spots) in the tank.

2.5. The GRASP Laboratory Blimp

At the University of Pennsylvania, we have been focused on developing a computer architecture and associated control and planning algorithms [30] to support our 3D multi-vehicle testbed (see Figure 3). This testbed centers on our 9 m. airship, which acts in concert with several ground-based mobile vehicles (Clodbusters). GRASP blimp is equipped with articulated electric motors, on-board computer, and sensors, including GPS, IMU, and several cameras. An on-board laptop communicates with a ground station via a wireless Ethernet link.

We have designed a feedback control algorithm for waypoint to waypoint navigation of an outdoor blimp and proposed an RRT-based algorithm for verification of the control law [36]. The algorithm systematically searches the set of all disturbances to validate viability of the control law in the presence of winds. Experimental results with a simulator show that RRT method can be effective in verifying controller design under unpredictable but bounded disturbances. This study was motivated by the results of relatively straightforward test, illustrated in Figure 4, to ascertain if the worst case disturbance affecting the trajectory of an airship could be predicted by assessing the effect of a disturbance with respect to degrees of freedom that are not directly controllable as the ship is under-actuated. As presented in Figure 4, the effects of an adversely gamed random disturbance can exceed those for which the ship has no direct actuation to react. Thus, we are interested in developing a suitable paradigm and algorithms for the performance evaluation of feedback controllers. Because disturbances such as those caused by wind gusts can be random, it is natural to think of randomized algorithms for simulation that can be designed to find worst case wind conditions. As noted, our approach uses the Rapidly-exploring Random Tree (RRT) algorithm, a randomized algorithm that has been found to be successful in a broad class of motion planning problems. It is well suited to the problem of quickly searching high-dimensional spaces that have both algebraic and differential constraints. The key idea is to bias the exploration toward unexplored portions of the space by sampling points in the state space, and incrementally pulling the search tree toward them. At the same time, it is possible to bias the search toward unsafe sets allowing us to explore the worst case inputs (or disturbances) via simulation. Our interest lies in the implementation of RRTs for the performance evaluation and validation of the feedback control law by searching the set of disturbances systematically. The method allows us to consider the second order dynamics of the airship as well as constraints imposed by the under-actuated system. We design a suitable metric that reflects these constraints for searching the configuration space. In addition, we explore a range of sampling strategies for the disturbance space and the configuration space.

The study outlined in [36] documents the development of the RRT algorithms for this application. Simulation results were presented for specific examples, such as the cases below in Figure 5. The randomized method allows us to obtain worst case bounded uncertainties (direction-changing wind field), which drive the airship to undesired regions. Such a worst case analysis is difficult to perform analytically or by intuition. Our on-going work addresses experiments in various wind conditions with feedback control laws for more complicated missions.

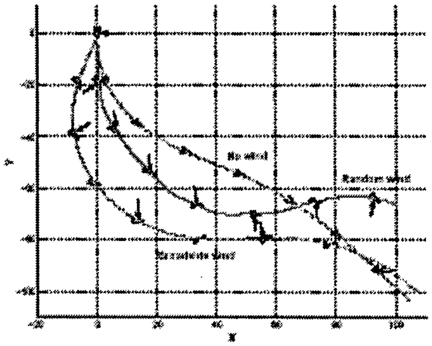

Figure 4: Comparison of broadside wind and random wind disturbance (arrows mean wind vectors acting on the hull of the blimp). The max.velocity of the wind is 0.5*m/sec*.

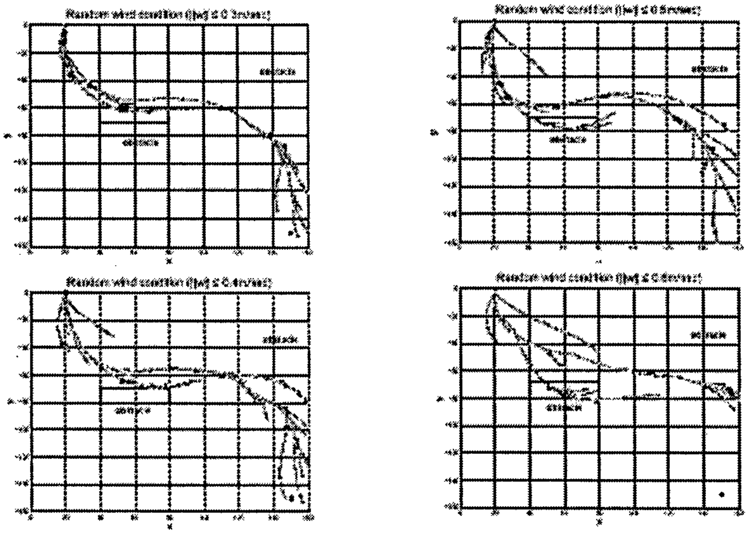

Figure 5: RRT's of the Blimp under various wind conditions as listed

3. Acknowledgment/Disclaimer

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number F49620-01-1-0382. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

4. Personnel Supported or Associated

Vijay Kumar	Professor, University of Pennsylvania
Naomi Leonard	Professor, Princeton University
Erdinc Altug	Graduate Student, University of Pennsylvania
Ralf Bachmayer	Post-doctoral fellow, Princeton University
Calin Belta	Graduate Student, University of Pennsylvania
Aveek Das	Graduate Student, University of Pennsylvania

Joel Esposito	Professor, U. S. Naval Academy
Edward Fiorelli	Graduate Student, Princeton University
Joshua Graver	Graduate Student, Princeton University
James F. Keller	Manager, Research Projects, University of Pennsylvania
Jongwoo Kim	Graduate Student, University of Pennsylvania
Benjamin Nabet	Visiting Student, ENAC, Toulouse, France
Sujit Nair	Graduate Student, Princeton University
Peter Ogren	Graduate Student, KTH, Sweden
Derek Paley	Graduate Student, Princeton University
Rodolphe Sepulchre	Visiting Professor, University of Liege, Belgium
Peng Song	Graduate Student, University of Pennsylvania
Fan Zhang	Graduate Student, University of Pennsylvania

5. Interactions

Kumar and Leonard have engaged in several collaborative activities that have involved researchers at the University of Pennsylvania, Princeton University and other organizations. Some of these activities are listed below:

- Leonard was an Invited Lecturer at Lund Institute of Technology, Sweden, Royal Institute of Technology, Sweden, Kristianstad University, Sweden, Swedish Defence Research Agency (FOI)
- Kumar and Leonard have participated in special sessions on groups of vehicles organized at SIAM 2001, CDC 2001, CDC 2002, MTNS 2002, SIAM 2003.
- Penn and Princeton have engaged in many collaborative activities. Research meetings have been held at Gainesville (2001), Las Vegas (2002), Snowbird (2003), Block Island (2003) and Philadelphia (2003).
- Kumar and Leonard (in collaboration with Professor Morse, Yale University) organized the Block Island Workshop on Cooperative Control, in June 2003. This workshop drew over 60 participants from different fields including AI, control theory, networking, and robotics.
- Leonard served on Penn Ph.D. candidate, Calin Belta's thesis committee.
- Kumar was a Distinguished Lecturer at the Department of Mechanical Engineering, Tokyo Institute of Technology, in June 2003.

6. Publications acknowledging AFOSR funding

[1] D.E. Chang, A.M. Bloch, N.E. Leonard, J.E. Marsden and C.A. Woolsey, "The equivalence of controlled Lagrangian and controlled Hamiltonian systems," *ESIAM: Control, Optimization and Calculus of Variations*, Vol. 8, 2002, 393-422.

[2] M. Chyba, N.E. Leonard and E.D. Sontag, "Singular trajectories in multi-input time-optimal problems: Application to controlled mechanical systems," *J. of Dynamical and Control Systems*, Vol 9, No. 1, 2003, 73-88.

[3] P. Ogren and N.E. Leonard, "A Provably Convergent Dynamic Window Approach to Navigation", *Proc. IFAC World Congress*, 2002.

[4] P. Ogren and N.E. Leonard, "Obstacle Avoidance in Formation", *Proceedings of the 2003 IEEE International Conference on Decision and Control,* Mauii, Hawaii, December 9-12, 2003

[5] P. Ogren, E. Fiorelli and N.E. Leonard, "Formations with a Mission: Stable Coordination of Vehicle Group Maneuvers", *Proc. 15th International Symposium on Mathematical Theory of Networks and Systems,* August, 2002.

[6] E. Fiorelli, P. Bhatta, N.E. Leonard and I.Shulman, Adaptive Sampling Using Feedback Control of an Autonomous Underwater Glider Fleet", *Proceedings 13th International Symposium on Unmanned Untethered Submersible Technology,* Durham NH, 2003.

[7] L. Moreau, R. Bachmayer and N.E. Leonard, "Coordinated gradient descent: a case study of Lagrangian dynamics with projected gradient information", *Proceedings, 2nd IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control*, Seville, Spain, April 2003.

[8] R. Bachmayer and N.E. Leonard, "Vehicle Networks for Gradient Descent in a Sampled Environment *Proc. IEEE CDC*, Las Vegas, 2002.

[9] P. Bhatta and N.E. Leonard, "Stabilization and Coordination of Underwater Gliders", *Proc. IEEE CDC*, Las Vegas, 2002.

[10] P. Ogren and N.E. Leonard, "A Tractable Convergent Dynamic Window Approach to Obstacle Avoidance," *Proc. IROS*, Switzerland, 2002.

[11] S. Nair and N.E. Leonard, "A Normal Form for Energy Shaping: Application to the Furuta Pendulum", *Proc IEEE CDC*, Las Vega, 2002.

[12] S. Nair , N.E.Leonard and L. Moreau, "Coordinated Control of Mechanical Systems with Unstable Dynamics*", Proc. IEEE CDC*, 2003.

[13] P. Ogren, E. Fiorelli and N.E. Leonard, "Cooperative Control of Mobile Sensor Networks: Adaptive Grading Climbing in a Distributed Environment," *IEEE Transactions on Automatic Control*, Vol. 49, No. 8, 2004, 1292-1302.

[14] P. Ogren and N.E. Leonard, "A Convergent Dynamic Window Approach to Obstacle Avoidance", *IEEE Transactions on Robotics and Automation*, in press, 2004.

[15] H. Hanssmann, N.E. Leonard and T.R. Smith, "Symmetry and Reduction for Coordinated Rigid Bodies," under review, 2004.

[16] S. Nair and N.E. Leonard, "Stabilization of a Coordinated Network of Rotating Rigid Bodies", *Proc. IEEE CDC*, 2004, to appear.

[17] R. Sepulchre, D. Paley and N. Leonard, "Collective Motion and Oscillator Synchronization", *in Proc. 2003 Block Island Workshop on Cooperative Control*, eds. V. Kumar, N. Leonard, A.S. Morse, Springer-Verlag, 2004, in press.

[18] D. Paley, N. Leonard and R. Sepulchre, "Collective Motion: Bistability and Trajectory Tracking," *Proc. IEEE CDC*, 2004, to appear.

[19] E. Fiorelli, N.E. Leonard, P. Bhatta, D. Paley, R. Bachmayer and D. Fratantoni, "Multi-AUV Control and Adaptive Sampling in Monterey Bay," *Proc. IEEE Autonomous Underwater Vehicles 2004: Workshop on Multiple AUV Operations (AUV04)*, Sebasco, ME, June 2004.

[20] C. Woolsey, C.K. Reddy, A.M. Bloch, D.E. Chang, N.E. Leonard and J.E. Marsden, "Controlled Lagrangian Systems with Gyroscopic Forcing and Dissipation," provisionally accepted for publication.

[21] J.M. Esposito and V. Kumar, "A method for modifying closed loop motion plans to satisfy unpredictable dynamic constraints at runtime", *Proc. IEEE ICRA*, Washington D.C., May 2002 (One of three finalists for the Best Paper Award).

[22] C. Belta and V. Kumar, "Trajectory design for formations of robots by kinetic energy shaping," *Proc. IEEE ICRA*, Washington D.C., May 2002.

[23] P. Song and V. Kumar, "A Potential Field Based Approach to Multi-Robot Manipulation," *Proc. IEEE ICRA*, Washington D.C., May 2002.

[24] Z. Wang and V. Kumar, "A Decentralized Test for Object Closure by Multiple Cooperating Mobile Robots," *Sixth International Symposium on Distributed Autonomous Robotic Systems*, DARS 2002, Fukuoka, Japan, June 25-27, 2002 (Conference Best Paper Award).

[25] H.G. Tanner, V. Kumar and G. Pappas, "The effect of Feedback and Feedforward on Formation ISS," *Proc. IEEE ICRA*, pp 3448-3453, Washington DC, May, 2002.

[26] C. Belta and V. Kumar, "A SVD-Based Projection method for interpolation on SE(3)," IEEE Transactions on Robotics and Automation, Vol. 18, No. 3, June 2002.

[27] A. Das, R. Fierro, V. Kumar, J. Ostrowski, J. Spletzer, and C.J. Taylor, "A Vision Based Formation Control Framework," *IEEE Transactions on Robotics and Automation: Multi Robot Systems*, October, 2002.

[28] G. Pereira, V. Kumar, and M. Campos, "Cooperative transport of planar objects by multiple mobile robots using object closure," 8th International Symposium on Experimental Robotics (ISER '02), Sant'Angelo d'Ischia, Italy, 8-11 July 2002.

[29] H.G. Tanner, V. Kumar and G. Pappas, "Stability Properties of Interconnected Vehicles," 15th International Symposium on Mathematical Theory of Networks and Systems, South Bend, IN, Aug 12-16, 2002.

[30] A. Das, J. Spletzer, V. Kumar and C. J. Taylor, "Ad Hoc Networks for Localization and Control," *Proc. IEEE CDC*, Las Vegas, 2002.

[31] E. Altug, J. Ostrowski, and R. Mahoney, "Control of a quadrotor helicopter using visual feedback," *Proc. IEEE ICRA*, Washington D.C., May 2002.

[32] G. A. S. Pereira, V. Kumar, and M. F. M. Campos, "Decentralized Algorithms for Multirobot Manipulation via Caging," in *Proceedings of the Fifth International Workshop on Algorithmic Foundations of Robotics* (*WAFR'02*), pp. 242-258, (Nice, France), December 2002.

[33] A. Das, R. Fierro, V. Kumar, J. Ostrowski, J. Spletzer, and C. J.Taylor, Vision Based Formation Control of Multiple Robots, Vol. 18, No.5, IEEE Transactions on Robotics and Automation, October 2002: 813-825.

[34] R. Alur, T. Dang, J. Esposito, Y. Hur, F. Ivancic, V. Kumar, I. Lee, P. Mishra, G. Pappas, and O. Sokolsky: Hierarchical Modeling and Analysis of Embedded Systems, Proceedings of the IEEE, (Volume 91,Number 1), January 2003.

[35] G. A. S. Pereira, V. Kumar, and M. F. M. Campos, "Decentralized Algorithms for Multirobot Manipulation via Caging," in Proceedings of the Fifth International Workshop on Algorithmic Foundations of Robotics (WAFR'02), pp. 242-258, (Nice, France), December 2002.

[36] J. Kim, J. Keller, V. Kumar, "Design and Verification of Controllers for Airships", Proceedings, IROS 2003, Las Vegas NV

[37] F. Zhang, B. Grocholsky, and V. Kumar, "Formations for Localization of Robot Networks", in *Proceedings of International Conference on Robotics and Automation*, New Orleans, Louisiana, 2004.

[38] F. Zhang, V. Kumar, and G.A.S. Pereira, "Necessary and Sufficient Conditions for Localization of Multiple Robot Platforms", in *Proceedings of ASME Design Engineering Technical Conferences*, Salt Lake City, Utah, 2004. (Finalist in DETC Best Paper Competition 2004)

[39] F. Zhang, B. Grocholsky, V. Kumar, and M. Mintz, "Cooperative Control for Localization of Mobile Sensor Networks", in *Proceedings of 2003 Block Island Workshop on Cooperative Control*, eds. V. Kumar, N. Leonard, A.S. Morse, Springer-Verlag, 2004.

7. Honors/Awards (Sept 2002 – August 2004)

- ASME Fellow (Kumar)
- Best Paper Award to Z. Wang and V. Kumar for the paper "A Decentralized Test for Object Closure by Multiple Cooperating Mobile Robots," at the *Sixth International Symposium on Distributed Autonomous Robotic Systems*, in Fukuoka, Japan, 2002.
- Plenary Talk at SIAM Conference on Applications of Dynamical Systems, Snowbird, UT, May 27-31, 2003. (Leonard)
- Calin Belta, who recently completed his Ph.D. at the University of Pennsylvania, accepted a faculty position as an Assistant Professor at Drexel University of Pennsylvania.
- Joel Esposito, who recently completed his Ph.D. at the University of Pennsylvania, accepted a faculty position as an Assistant Professor at the U. S. Naval Academy
- Finalist for the DETC Best Paper Award to F. Zhang, V. Kumar, and G.A.S. Pereira, for the paper, "Necessary and Sufficient Conditions for Localization of Multiple Robot Platforms", in *Proceedings of ASME Design Engineering Technical Conferences*, Salt Lake City, Utah, 2004.
- Kayamori Best Paper Award, IEEE Int. Conference on Robotics and Automation (2004), with Peng Song, Jeffrey Trinkle and Jong-Shi Pang.

8. Transitions

Leonard's work is being applied in the Autonomous Ocean Sampling Network project's Predictive Skills Experiment in Monterey Bay, August-September 2003. See http://www.princeton.edu/~dcsl/aosn.

Kumar is collaborating with Evolution Robotics on 3-D vision for navigation. Evolution Robotics has provided their software development kit (valued at $40,000) for the development of new algorithms for vision-based control.

NRL (Alan Schulz), ARL (Phil Emmerman) and AFRL (Siva Banda, Rob Murphey) personnel have visited our labs and provided valuable feedback on our work and input that has helped shape our research directions.

Belta, a recent Ph.D. from the University of Pennsylvania, accepted a faculty position as an Assistant Professor at Drexel University. Esposito, a recent Ph.D. from the University of Pennsylvania, is now an assistant professor at the U.S. Naval Academy. Patel, who is a recent Ph.D. from the University of Pennsylvania, is now an assistant professor at the U.S. Naval Academy.