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OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 01-06-2011	2. REPORT TYPE FINAL TECHNICAL	3. DATES COVERED (From - To) 01/01/2007-09/30/2010
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4. TITLE AND SUBTITLE Algorithmic Coordination in Robotic Networks	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-07-1-0721
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Bullo, Francesco, Dr.	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Regents of the University of California Office of Research 3227 Cheadle Hall Santa Barbara, CA 93106-2050	8. PERFORMING ORGANIZATION REPORT NUMBER
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Arlington, VA 22203-1995	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

20110119495

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research focuses on developing a broad theoretical modeling framework for robotic networks with a rich application catalog of combinatorial and geometric tasks. For a detailed realistic model combining mobile robotics and ad hoc wireless networking, the design and analysis of algorithms with appropriate performance, robustness and scalability properties for various task allocation, surveillance, and information gathering applications is envisioned.

15. SUBJECT TERMS
robotic networks

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON Bullo, Francesco, Dr.
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (805) 893-5169

Final Progress Report

ONR Grant # N00014-07-1-0721

“Algorithmic Coordination in Robotic Networks”

Dates Covered: 6/1/2007 — 9/30/2010

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November 29, 2010

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1 Original Proposal Summary

This research focuses on developing a broad theoretical modeling framework for robotic networks with a rich application catalog of combinatorial and geometric tasks. For a detailed realistic model combining mobile robotics and ad hoc wireless networking, we envision designing and analyzing algorithms with appropriate performance, robustness and scalability properties for various task allocation, surveillance, and information gathering applications.

The focus of this proposal is twofold. The first set of deliverables is related to the development of a general modeling framework for robotic networks. The second set of deliverables is related to the development of a class of distributed algorithms for target assignments; based on the classic auction algorithms in static networks, we intend to design efficient algorithms in worst case, stochastic and dynamic environments. Specific deliverables include:

1. an algorithmic theory of robotic networks; we aim to provide a formal model of communication, control, and computation and establish rigorous performance bounds for basic robotic tasks, such

as deployment and rendezvous. We aim to provide a full suite of results on: time, communication, space and energy complexity for algorithms that tolerate processor and communication failures in face of wireless and physical congestion.

2. efficient algorithms for target assignment and formation control; we envision the design of efficient algorithms to divide a group of known targets among the robots and, simultaneously, steer each robot to its target set. At its heart, this is a combinatorial problem to be solved in a distributed receding-horizon manner. In this context we will consider various possible information patterns available to the agents, stochastic and dynamic scenarios, and sensor-based tasks, e.g., networks with visibility, electromagnetic and/or acoustic sensors.

From a technical viewpoint, the key challenge lies at the intersection of distributed computation, combinatorial optimization, computational geometry, and control theory.

2 Technical Accomplishments

We begin with a schematic description of the technical work completed as fully or partly supported by this award. The results are organized in four main thrusts:

1. dynamic vehicle routing and target assignment,
2. distributed deployment and partitioning,
3. theory of robotic networks and distributed optimization, and
4. other robotic coordination algorithms.

The journal publications, listed in Section 3, are organized in the same four thrusts.

2.1 Dynamic vehicle routing and target assignment

Supported by this grant, we developed novel concepts and algorithms for dynamic vehicle routing (DVR), that is, for the automatic planning of optimal multi-vehicle routes to perform tasks that are generated over time by an exogenous process. We considered a rich variety of scenarios relevant for robotic applications. The basic DVR problem is stated as follows: demands for service arrive at random locations at random times and a vehicle travels to provide on-site service while minimizing the expected wait time of the demands. Throughout the course of this grant, we have treated different multi-vehicle scenarios based on different models for demands (e.g., demands with different priority levels and impatient demands), vehicles (e.g., motion constraints, communication and sensing capabilities), and tasks. The performance criterion used in these scenarios is either the expected wait time of the demands or the fraction of demands serviced successfully. In each specific DVR scenario, we adopted a rigorous technical approach that relies upon methods from queueing theory, combinatorial optimization and stochastic geometry. First, we establish fundamental limits on the achievable performance, including limits on stability and quality of service. Second, we design algorithms, and provide provable guarantees on their performance with respect to the fundamental limits.

Specific results include the following. Article [J2] contains a comprehensive theory of static assignment problems for robotic networks. Article [J3] deals with the dynamic team forming problem, in which targets require simultaneous servicing by teams of robots with distinct capacities. Article [J4] proposes cooperative routing policies that take into explicit account the nonholonomic constraints of aerial vehicles. Article [J5] proposes cooperative routing policies that efficiently handle distinct priorities in the targets to be serviced. Article [J6] is the first article to propose policies for moving targets the proposed policies are polynomial time and come with performance guarantees. Finally, article [J7] is a survey article that neatly organizes all results in a unique reference.

2.2 Distributed deployment and partitioning

Deployment, partitioning and coverage control problems have been a strong interest since our highly cited original article in the *IEEE Transactions on Robotics and Automation* in 2004. During this period, we have made a number of important advances. First, from an educational viewpoint, we completed and published our monograph on this topic, reference [B1].

Second, in references [J9] and [J12], we have proposed novel distributed algorithms that require only short-range, unreliable pairwise “gossip” communication between the agents. The algorithms 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. Our theoretical analysis, based on a dynamical system on partitions of the graph’s vertices, shows that the territory partition converges to a centroidal Voronoi partition in finite time. A key innovative idea is describing coverage algorithms for robot deployment and environment partitioning as dynamical systems on a space of partitions. In other words, we study the evolution of the regions assigned to each agent rather than the evolution of the agents’ positions. We also establish scalability properties for the algorithm and describe how it can be implemented on robots with limited computational resources. We have implemented it using the Player/Stage robot control system, and developed both large-scale simulations in complex environments as well as hardware experiments in our lab.

We have also made progress in a number of related directions. In article [J8], we propose distributed and adaptive algorithms for equitable partitioning. Equitable partitioning is related to load balancing in dynamic vehicle routing and in other robotic spatial tasks. Article [J10] proposes robot placement strategies and environment partitioning policies for the purpose of intercepting moving targets. Finally, article [J11] proposes distributed deployment algorithms for visibility coverage in polygonal environments with holes; the algorithms are related to our previous work on the distributed art gallery problem and are the first to obtain rigorous bounds on the number of required agents and complete visibility guarantees.

2.3 Theory of robotic networks and distributed optimization

We continued our work on a general theory of robotic networks. Beginning with two joint articles in the *IEEE Transactions on Automatic Control* (supported by a previous ONR grant), we presented a more comprehensive theory in the text [B1]. We also addressed various quantization problems in the two references [J13] and [J14].

Finally, on a partly related directions, we have recently developed a novel distributed solver for abstract linear programs. Distributed abstract programs are a novel class of distributed optimization problems that generalize linear programs, support vector machine training, learning problems, and various geometric optimization problems. Journal article [J15] proposes novel “constraints consensus algorithms” that are appropriate for networks with weak time-dependent connectivity requirements and tight memory constraints.

2.4 Other robotic coordination algorithms

In references [J16], [J17] and [J18] we pursued other research directions. In reference [J16], we address discrete-time pursuit-evasion games in the plane, where every player has identical sensing and motion ranges; we propose a Sweep-Pursuit-Capture pursuer strategy to capture the evader and apply it to two variants of the game. In reference [J17] we propose algorithms that compute polygon approximations for convex contours; this geometric optimization problem is relevant in interpolation theory, data compression, and has potential applications in robotic sensor networks. In reference [J18] we study the visibility-maintenance problem for a leader-follower pair of aerial vehicles with input constraints, and propose an original solution based on the notion of controlled invariance.

3 List of Publications Supported by this Contract

Publications are organized by themes and are listed in rough chronological order. The list includes a few recent journal articles that have been submitted and but not yet accepted.

Manuscript

- [B1] F. Bullo, J. Cortés, and S. Martínez, *Distributed Control of Robotic Networks*. Applied Mathematics Series, Princeton University Press, 2009. Available at <http://www.coordinationbook.info> (4644 downloads during period 4jun08-3may10)

Papers published in peer-reviewed journals: Target Assignment and Dynamic Vehicle Routing

- [J2] S. L. Smith and F. Bullo, "Monotonic target assignment for robotic networks," *IEEE Transactions on Automatic Control*, vol. 54, no. 9, pp. 2042–2057, 2009
- [J3] S. L. Smith and F. Bullo, "The dynamic team forming problem: Throughput and delay for unbiased policies," *Systems & Control Letters*, vol. 58, no. 10-11, pp. 709–715, 2009
- [J4] J. J. Enright, K. Savla, E. Frazzoli, and F. Bullo, "Stochastic and dynamic routing problems for multiple UAVs," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 34, no. 4, pp. 1152–1166, 2009
- [J5] S. L. Smith, M. Pavone, F. Bullo, and E. Frazzoli, "Dynamic vehicle routing with priority classes of stochastic demands," *SIAM Journal on Control and Optimization*, vol. 48, no. 5, pp. 3224–3245, 2010
- [J6] S. D. Bopardikar, S. L. Smith, F. Bullo, and J. P. Hespanha, "Dynamic vehicle routing for translating demands: Stability analysis and receding-horizon policies," *IEEE Transactions on Automatic Control*, vol. 55, no. 11, 2010. (Submitted, Mar 2009) to appear
- [J7] F. Bullo, E. Frazzoli, M. Pavone, K. Savla, and S. L. Smith, "Dynamic vehicle routing for robotic systems," *Proceedings of the IEEE*, May 2010. Submitted

Papers published in peer-reviewed journals: Distributed Deployment and Partitioning

- [J8] M. Pavone, A. Arsie, E. Frazzoli, and F. Bullo, "Distributed algorithms for environment partitioning in mobile robotic networks," *IEEE Transactions on Automatic Control*, 2010. (Submitted Dec 2008 and Aug 2009) to appear
- [J9] F. Bullo, R. Carli, and P. Frasca, "Gossip coverage control for robotic networks: Dynamical systems on the the space of partitions," *SIAM Journal on Control and Optimization*, Aug. 2010. Submitted
- [J10] S. D. Bopardikar, S. L. Smith, and F. Bullo, "On vehicle placement to intercept moving targets," *Automatica*, Mar. 2010. Submitted
- [J11] K. J. Obermeyer, A. Ganguli, and F. Bullo, "Multi-agent deployment for visibility coverage in polygonal environments with holes," *International Journal on Robust and Nonlinear Control*, Sept. 2010. Submitted
- [J12] J. W. Durlham, R. Carli, P. Frasca, and F. Bullo, "Discrete partitioning and coverage control for gossiping robots," *IEEE Transactions on Robotics*, Nov. 2010. Submitted

Papers published in peer-reviewed journals: Theory of Robotic Networks and Distributed Optimization

- [J13] R. Carli and F. Bullo, "Quantized coordination algorithms for rendezvous and deployment," *SIAM Journal on Control and Optimization*, vol. 48, no. 3, pp. 1251–1274, 2009
- [J14] R. Carli, F. Bullo, and S. Zampieri, "Quantized average consensus via dynamic coding/decoding schemes," *International Journal on Robust and Nonlinear Control*, vol. 20, no. 2, pp. 156–175, 2010
- [J15] G. Notarstefano and F. Bullo, "Distributed abstract optimization via constraints consensus: Theory and applications," *IEEE Transactions on Automatic Control*, Oct. 2009. Submitted

Papers published in peer-reviewed journals: Other Coordination Algorithms

- [J16] S. D. Bopardikar, F. Bullo, and J. P. Hespanha, "On discrete-time pursuit-evasion games with sensing limitations," *IEEE Transactions on Robotics*, vol. 24, no. 6, pp. 1429–1439, 2008
- [J17] S. Susca, F. Bullo, and S. Martínez, "Gradient algorithms for polygonal approximation of convex contours," *Automatica*, vol. 45, no. 2, pp. 510–516, 2009
- [J18] F. Morbidi, F. Bullo, and D. Prattichizzo, "Visibility maintenance via controlled invariance for leader-follower vehicle formations," *Automatica*, June 2010. (Submitted Dec 2009) under review

Papers published in conference proceedings or as book chapters

- [C19] G. Notarstefano and F. Bullo, "Network abstract linear programming with application to minimum-time formation control," in *IEEE Conf. on Decision and Control*, (New Orleans, LA), pp. 927–932, Dec. 2007
- [C20] S. Susca, F. Bullo, and S. Martínez, "Synchronization of beads on a ring," in *IEEE Conf. on Decision and Control*, (New Orleans, LA), pp. 4845–4850, Dec. 2007
- [C21] S. D. Bopardikar, F. Bullo, and J. P. Hespanha, "A cooperative Homicidal Chauffeur game," in *IEEE Conf. on Decision and Control*, (New Orleans, LA), pp. 4857–4862, Dec. 2007
- [C22] M. Pavone, E. Frazzoli, and F. Bullo, "Decentralized algorithms for stochastic and dynamic vehicle routing with general demand distribution," in *IEEE Conf. on Decision and Control*, (New Orleans, LA), pp. 4869–4874, Dec. 2007
- [C23] S. L. Smith and F. Bullo, "Dynamic multi-agent team forming: Asymptotic results on throughput versus delay," in *American Control Conference*, (Seattle, WA), pp. 1406–1411, June 2008
- [C24] S. D. Bopardikar, F. Bullo, and J. P. Hespanha, "A pursuit game with range-only measurements," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 4233–4238, Dec. 2008
- [C25] G. Piovan, I. Shames, B. Fidan, F. Bullo, and B. D. O. Anderson, "On frame and orientation localization for relative sensing networks," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 2326–2331, Dec. 2008
- [C26] R. Carli, F. Bullo, and S. Zampieri, "Quantized average consensus via dynamic coding/decoding schemes," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 4916–4921, Dec. 2008
- [C27] F. Morbidi, F. Bullo, and D. Prattichizzo, "On visibility maintenance via controlled invariance for leader-follower Dubins-like vehicles," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 1821–1826, Dec. 2008

- [C28] M. Pavone, E. Frazzoli, and F. Bullo, "Distributed policies for equitable partitioning: Theory and applications," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 4191–4197, Dec. 2008
- [C29] K. Plarre and F. Bullo, "Increasingly correct message passing averaging algorithms," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 1304–1310, Dec. 2008
- [C30] S. D. Bopardikar, S. L. Smith, F. Bullo, and J. P. Hespanha, "Dynamic vehicle routing with moving demands – Part I: Low speed demands and high arrival rates," in *American Control Conference*, (St. Louis, MO), pp. 1454–1459, June 2009
- [C31] S. L. Smith, S. D. Bopardikar, F. Bullo, and J. P. Hespanha, "Dynamic vehicle routing with moving demands – Part II: High speed demands or low arrival rates," in *American Control Conference*, (St. Louis, MO), pp. 1466–1471, June 2009
- [C32] P. Frasca, R. Carli, and F. Bullo, "Multiagent coverage algorithms with gossip communication: Control systems on the space of partitions," in *American Control Conference*, (St. Louis, MO), pp. 2228–2235, June 2009
- [C33] S. L. Smith, M. Pavone, F. Bullo, and E. Frazzoli, "Dynamic traveling repairperson with priority demands," in *IEEE Conf. on Decision and Control*, (Cancún, México), pp. 1206–1211, Dec. 2008
- [C34] M. Pavone, S. L. Smith, F. Bullo, and E. Frazzoli, "Dynamic multi-vehicle routing with multiple classes of demands," in *American Control Conference*, (St. Louis, MO), pp. 604–609, June 2009
- [C35] S. L. Smith, S. D. Bopardikar, and F. Bullo, "A dynamic boundary guarding problem with translating demands," in *IEEE Conf. on Decision and Control*, (Shanghai, China), pp. 8543–8548, Dec. 2009
- [C36] J. W. Durham, R. Carli, P. Frasca, and F. Bullo, "Discrete partitioning and coverage control with gossip communication," in *ASME Dynamic Systems and Control Conference*, (Hollywood, CA), Oct. 2009
- [C37] S. D. Bopardikar, S. L. Smith, and F. Bullo, "Vehicle placement to intercept moving targets," in *American Control Conference*, (Baltimore, MD), pp. 5538–5543, June 2010

4 Scientific Personnel

- Francesco Bullo, PI
- Stephen Smith, supported as PhD student at least 2 years, now postdoc at MIT, Assistant Professor at University of Waterloo beginning March 2011
- Shammak D. Bopardikar, supported as PhD student at least 1 year, now postdoc at UCSB
- Joseph W. Dirham, supported as PhD student at least 2 years, expected graduation April 2011
- Paolo Frasca and Fabio Morbidi, visiting PhD students, now postdocs at University of Torino and Northwestern University, respectively

Collaboration with other scientists, not supported on this grant:

- Ruggero Carli, now Assistant Professor at University of Padova
- Marco Pavone, now Research Scientists at JPL
- Giuseppe Notarstefano, now Assistant Professor at University of Lecce

5 Research Awards and Honors

The following awards were received by the PI and his group during the award period:

- Plenary Speaker:
 - 3rd IEEE Multi-Conference in Systems and Control (MSC), Saint Petersburg, Russia, Jul 2009
- SemiPlenary or Keynote Speaker:
 - 2nd IFAC Workshop on Distributed Estimation and Control in Networked Systems, Annecy, France, Sep 2010
 - Symposium on Recent Trends in Networked Systems and Cooperative Control, Stuttgart, Germany, Sep 2009
 - 5th International Conference on Applied Mathematics and Computing, Plovdiv, Bulgaria, Aug 2008
- IEEE Fellow, Class of 2010
- Article selection for inclusion in SIGEST section of SIAM Review, Mar 2009
- Outstanding Paper Award, IEEE Control Systems Magazine, 2008
- Best Student Paper Award Winner (as advisor): ACC 2006, ACC 2010
- Best Student Paper Award Finalist (as advisor): CDC 2007
- Best PhD Thesis Award, CCDC, UCSB (as advisor)
- Primo Professor, Kiosk UCSB Student Handbook, 2008-2010
- Outstanding Faculty Member, Mechanical Engineering, UCSB, Spring 2008
- Invited Lecturer, Summer School of Automatic Control, Grenoble, France, Sep 2010
- Invited Lecturer, Summer School on Networked Control Systems, Siena, Italy, Jul 2009

Selected Invited Lectures

- (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 Supélec (France), UC Irvine
- (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, NE{S|T}COC Symposium), ETH Zürich (Switzerland)
- (2008): UC San Diego (ITA Workshop), University of Siena (Italy), University of Pisa (Italy), UC Los Angeles, Yale University, City College of New York, University of Pennsylvania, Massachusetts Institute of Technology, Yale University (Frontiers in Distributed Communication, Sensing and Control Workshop), Johns Hopkins University
- (2007): University of Illinois, Georgia Tech (RSS Workshop on Robotic Sensor Networks), Australian National University (Canberra, ACT)

6 Report of Patents and Inventions

None.