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13. ABSTRACT (Maximum 200 words)

This report describes the initial months of a multi-university research effort to develop the technological foundations of Communicating Networked Control Systems. Coordinated efforts at four participating institutions are reported here, and in summary form, highlights of each team member's work are reported together with a discussion of interrelationships among the different efforts. The combined work of the participating institutions has led to significant progress in (i) the control theory and applications of feedback systems involving rate-limited communications channels, (ii) the allocation of bandwidth and other resources in networked control systems, (iii) ad hoc optical communications networks, (iv) the geometric foundations and information processing requirements for controlled motions of fleets of UAV's, and (v) scheduling and routing policies for networked control systems which will guarantee stable operation. By maintaining good communication among the various teams, the multiuniversity center for Communicating Networked Control system has made a conscious effort to have each team's efforts support and complement those of the other teams. Specific collaborative activities will be described.

14. SUBJECT TERMS
data networks, real-time control, network resource allocation, communication protocols, QoS, network information theory, Bluetooth, information-based control, information-induced instability, wireless networks, ad hoc networks, UAV, leader/first-follower pair

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1. List of Manuscripts and Publications

Boston University

1. J. Baillieul, "Bi-Directional Electrostatic Actuator Operated with Charge Control," *Proceedings of the 2002 Joint Electrostatics Society of America/Institute of Electrostatics Japan Annual Conference*, June 25-28, 2002, Northwestern University, Evanston, IL (with T. Sugimoto, M. Horenstein, and K. Nonaka). (Also to be submitted to *Journal of Electrostatics* (Elsevier).)

2. J. Baillieul, "Feedback Designs in Information-based Control," *Stochastic Theory and Control* -Proceedings of Workshop held at the University of Kansas, Bozenna Pasik-Duncan (Ed.), Lecture Notes in Control and Information Sciences, Springer-Verlag, New York, 2002, pp. 35-57.

3. J. Baillieul, "Feedback Coding for Information-Based Control - Operating Near the Data-Rate Limit," in the *Proceedings of the 2002 IEEE Conference on Decision and Control*, Las Vegas, NV, December, 2002, pp. 3229-3236.

4. J. Baillieul and A. Suri, "Information Patterns and Hedging Brockett's Theorem in Controlling Vehicle Formations," submitted to the 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003. Preprint available: http://people.bu.edu/johnb/CDC03.1.pdf.

5. K. Li and J. Baillieul, "The Appropriate Quantization for Digital Finite Communication Bandwidth (DFCB) Control," submitted to the 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003. Preprint available: http://people.bu.edu/johnb/CDC03.2.pdf.

6. A.C. Smith and J. Baillieul, "Vortex Models for the Control of Stall," submitted to the 2003 *IEEE Conference on Decision and Control*, Maui, Hawaii, December, 2003. Preprint available: http://people.bu.edu/johnb/CDC03.3.pdf.

7. Perreault, J. A., Bifano, T. G., Levine, B.M., and Horenstein, M., "Adaptive optic correction using micro-electromechanical deformable mirrors," *Optical Engineering* [41]5, pp. 561-566, 2002.

8. Horenstein, M., Pappas, S., Fishov, A., and Bifano, T.G., "Electrostatic Micromirrors for Subaperturing in an Adaptive Optics System," *Journal of Electrostatics*, Vol. 54, pp. 321-332, 2002.

9. Weyrauch T., Vorontsov M. A., Bifano T. G., Hammer J. A., Cohen M., and Cauwenberghs G., "Microscale adaptive optics: wavefront control with a μ-mirror array and a VLSI stochastic gradient descent controller," *Applied Optics*, [40] 24 pp. 4243-4253, 2001.

10. Ch. Paschalidis, "Inventory Control for Supply Chains with Service Level Constraints: A Synergy between Large Deviations and Perturbation Analysis" (with Y. Liu, C.G. Cassandras, C. Panayiotou), January 2002; Revised November 2002, to appear *The Annals of Operations Research* (Special Volume on Stochastic Models of Production-Inventory Systems). Abstract: http://ionia.bu.edu/papers/rev_ld-pa-multi_abs.ps, or http://ionia.bu.edu/papers/rev_ld-pa-multi_abs.pdf,
Paper: http://ionia.bu.edu/papers/rev_ld-pa-multi.ps, or http://ionia.bu.edu/papers/rev_ld-pa-multi.pdf.

11. Ch. Paschalidis, "Target-Pursuing Policies for Multiclass Queueing Networks" (with C. Su and M.C. Caramanis), July 2002, submitted for publication.
Abstract: http://ionia.bu.edu/papers/qnets-target-abs.ps, or http://ionia.bu.edu/papers/qnets-target-abs.pdf
Paper: http://ionia.bu.edu/papers/qnets-target.ps, or http://ionia.bu.edu/papers/qnets-target.pdf.

12. Ch. Paschalidis, "Pricing in Multiservice Loss Networks: Static Pricing, Asymptotic Optimality, and Demand Substitution Effects" (with Y. Liu), *IEEE/ACM Transactions on Networking*, Vol. 10 (2002), No. 3, pages 425-438.
Abstract: http://ionia.bu.edu/papers/net-pricing-abs.ps or http://ionia.bu.edu/papers/net-pricing-abs.pdf. Paper (Revised 8/6/02): http://ionia.bu.edu/papers/net-pricing.ps or http://ionia.bu.edu/papers/net-pricing.pdf
Paper Companion: http://ionia.bu.edu/papers/net-pricing-compa.ps or http://ionia.bu.edu/papers/net-pricing-compa.pdf .

13. Ch. Paschalidis, "Large Deviations-based Asymptotics for Inventory Control in Supply Chains" (with Y. Liu), *Operations Research*, in print.
Abstract: http://ionia.bu.edu/papers/scm_abs.ps or http://ionia.bu.edu/papers/scm_abs.pdf .
Paper (Revised February 2002): http://ionia.bu.edu/papers/scm.ps or http://ionia.bu.edu/papers/scm.pdf

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Harvard University

1. Roger Brockett, "Pattern Generation and the control of Nonlinear Systems," Harvard University preprint. Submitted to the *IEEE Transactions on Automatic Control.*

2. Magnus Egersdtedt and Roger Brockett, "Feedback Can Reduce the Specification Complexity of Motor Programs," to appear in the *IEEE Transactions on Automatic Control,* February 2003.

University of Illinois

1. P.R. Kumar, "The Distributed Nonlinear Stochastic World of Networks." Control of Stochastic Systems. Submitted to Proceedings of the IUTAM Symposium on Nonlinear Stochastic Dynamics, Allerton Park, Monticello, Illinois, USA, August 26-30, 2002, October 13, 2002.

2. P.R. Kumar, "Ad Hoc Wireless Networks: From Theory to Protocols." Submitted for publication as an Invited Chapter in, Ad Hoc Wireless Networking, Edited by Xiuzhen Cheng, Xiao Huang and Ding-Zhu Du. To be published by Kluwer. October 13, 2002.

3. Piyush Gupta and P. R. Kumar, "Towards an Information Theory of Large Networks: An Achievable Rate Region." Submitted to *IEEE Transactions on Information Theory*. Revised Nov 13, 2002.
http://black.csl.uiuc.edu/~prkumar/ps_files/net_info.ps .

4. V. Borkar and P. R. Kumar, "Dynamic Cesaro-Wardrop Equilibration in Networks," To appear in *IEEE Transactions on Automatic Control*. Revised Nov 4, 2002. http://black.csl.uiuc.edu/~prkumar/ps_files/wardrop.ps.

5. Feng Xue and P. R. Kumar, ``The number of neighbors needed for connectivity of wireless networks." Submitted to Wireless Networks. April 1, 2002. http://black.csl.uiuc.edu/~prkumar/ps_files/connect.ps.

6. Liang-Liang Xie and P. R. Kumar, "A Network Information Theory for Wireless Communication: Scaling Laws and Optimal Operation." Submitted to *IEEE Transactions on Information Theory*. April 12, 2002. http://black.csl.uiuc.edu/~prkumar/ps_files/net_inf_theory.ps.

7. Kurt Plarre and P. R. Kumar, "Extended Message Passing Algorithm for Inference in Loopy Gaussian Graphical Models." Submitted to Computer Networks. October 15, 2002. http://black.csl.uiuc.edu/~prkumar/ps_files/net_inf_theory.ps.

8. S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar, "Power Control in Ad-Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW Protocol." Proceedings of the European Wireless Conference -- Next Generation Wireless Networks: Technologies, Protocols, Services and Applications, pp.156--162, Florence, Italy, Feb.~25--28, 2002. http://black.csl.uiuc.edu/~prkumar/ps_files/compow_ewc_2002.pdf.

9. Liang-Liang Xie and P. R. Kumar, ``New Results in Network Information Theory: Scaling Laws and Optimal Operational Modes for Wireless Networks." pp. 3205--3208, Proc. 41st IEEE Conference on Decision and Control, Las Vegas, Dec., 2002.

10. Vikas Kawadia and P. R. Kumar, "Power Control and Clustering in Ad Hoc Networks." To appear in INFOCOM 2003, April 1, 2003.

University of Maryland

1. E. W. Justh and P. S. Krishnaprasad, "Equilibria and steering laws for planar formations", submitted to *Systems and Control Letters*, September 2002.

2. E. W. Justh and P. S. Krishnaprasad, "A simple control law for UAV formation flying", Institute for Systems Research Technical Report, TR 2002-38, 35 pages. http://techreports.isr.umd.edu/TechReports/ISR/2002/TR_2002-38/TR_2002-38.phtml.

3. Fumin Zhang and P. S. Krishnaprasad, "Formation dynamics under a class of control laws", in Proceedings of 2002 American Control Conference, (May 8-12, Anchorage), pp 1678-1685. American Automatic Control Council, Philadelphia.

4. Fumin Zhang and P. S. Krishnaprasad, "Coordinated orbit transfer for satellite clusters", in *Proceedings of 41st IEEE Conference on Decision and Control*, (December 10-13, 2002, Las Vegas), pp 4095-4100, IEEE, New York.

5. S. Andersson and P. S. Krishnaprasad, "Degenerate gradient flows: a comparison study of convergence rate estimates", in *Proceedings of 41st IEEE Conference on Decision and Control*, (December 10-13, 2002, Las Vegas), pp. 4712-4717, IEEE, New York.

6. P.S. Krishnaprasad, "Control over a free-space optical channel", *Proceedings of 41st IEEE Conf. on Decision and Control*, (December 10-13, 2002, Las vegas), 2029-2031, IEEE, New York.

7. B. Azimi-Sadjadi and P. S. Krishnaprasad, "Approximate nonlinear filtering and its application in navigation", submitted to *Automatica*, April 2002.

8. B. Azimi-Sadjadi and P. S. Krishnaprasad, "Change detection for nonlinear systems: a particle filtering approach", in Proceedings of 2002 American Control Conference, (May 8-12, Anchorage), pp. 4074-4079, American Automatic Control Council, Philadelphia.

9. Handzel and P. S. Krishnaprasad, "Biomimetic sound source localization", *IEEE Sensors Journal*, vol. 2, no. 6, 10 pages, December 2002 (in press).

10. Fumin Zhang, Michael Goldgeier and P. S. Krishnaprasad, "Control of Small Formations Using Shape Coordinates", to appear in Proceedings of the IEEE Intl. Conference on Robotics and Automation, (May 12-17 Taipei, Taiwan, 2003), (6 pages).

11. D. Napoletani, C. A. Berenstein and P. S. Krishnaprasad, "Quotient signal decomposition and order estimation", Institute for Systems Research Technical Report, TR-2002-47. http://techreports.isr.umd.edu/TechReports/ISR/2002/TR_2002-47/TR_2002-47.pdf.

12. D. Hristu-Varsakelis and P.R. Kumar, "Interrupt-based feedback control over a shared communication medium," *Proc. of the IEEE Conference on Decision and Control*, 2002, p. 3223-8. Download: http://www.glue.umd.edu/~hristu/publications/CDC02_LC_final.pdf.

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14. B. Frankpitt and J.S. Baras, "Nonlinear Robust Control with Unknown System Models: HMM Formulation", submitted to *SIAM J. Control and Optimization*, 2002.

15. B. Frankpitt and J.S. Baras, "Nonlinear Robust Control with Unknown HMM Models: Convergence and Learning", submitted to *SIAM J. Control and Optimization*, 2002.

16. J.S. Baras, X. Tan and W. Xi, "Jointly Optimal Quantization, Estimation, and Control of Hidden Markov Chains", submitted to the *2003 IEEE Conference on Decision and Control*.

17. J.S. Baras, X. Tan, P. Hovareshti, "Decentralized Control of Autonomous Vehicles", submitted to the *2003 IEEE Conference on Decision and Control*.

2. Personnel

Faculty

1. John Baillieul, Boston University
2. Thomas Bifano, Boston University
3. Ioannis Ch. Paschalidis, Boston University
4. Roger Brockett, Harvard University
5. P.R. Kumar, University of Illinois
6. P.S. Krishnaprasad, University of Maryland
7. Prakash Narayan, University of Maryland
8. D. Hristu-Varsakelis, University of Maryland
9. John S. Baras, University of Maryland
10. E. W. Justh, University of Maryland

Visiting Scientists

University of Illinois - Jan H. van Schuppen

Post Doctoral Fellows

University of Maryland

1. Handzel, Post Doc.
2. B. Azimi-Sadjadi, Post Doc

PhD Students

Boston University:

1. Keyong Li, Ph.D. candidate, Department of Aerospace/Mechanical Engineering.
2. Atul S. Suri, Ph.D. candidate, Department of Aerospace/Mechanical Engineering, PhD Topic: Swarms of communicating mobile robots.
3. Yong Liu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (degree awarded May 2002).
4. Adam C. Smith, Ph.D. candidate, Department of Aerospace/Mechanical Engineering (supported through other means but working on problems related to the project).
5. Jeremy Grace, Ph.D. candidate, Department of Aerospace/Mechanical Engineering (supported through other means but working on problems related to the project).
6. Chang Su, Ph.D. candidate, Dept. of Manufacturing Eng
7. Jian Shao, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related tothe project).
8. Ying Liu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
9. Yimin Yu, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).
10. Jonghoon Jeong, Ph.D. candidate, Dept. of Manufacturing Eng., Boston University (supported through other means but working on problems related to the project).

Harvard University

1. Mohamed Belabbas, Ph.D. candidate
2. Hongyi Li, Ph.D. candidate
3. Abdol-Reza mansouri, Ph.D. candidate
4. Michael McLeroy, Ph.D. candidate
5. Denjamin Pierce, Ph.D. candidate
6. Jian Zou, Ph.D. candidate

University of Illinois

1. Arvind Giridhar, Ph.D. candidate
2. Binita Binita, PhD candidate
3. Robert A Rozovsky, PhD candidate
4. Yan Wu, PhD candidate

University of Maryland

1. P. Horvasheti, Ph.D. candidate.
2. Chang Zhang, Ph.D. candidate.
3. Lei Zhang, Ph.D. candidate.
4. Komaee, Ph.D. candidate.

5. K. Chakraborty, Ph.D. candidate.
6. D. Napoletani Ph.D. candidate.
7. Fumin Zhang Ph.D. candidate, (supported through other means but working on problems related to the project).
8. Sean Andersson Ph.D. candidate(supported through other means but working on problems related to the project).

M.S. Students

Boston University:

D.J. Raghunathan, MS candidate (Completion Jan. 2002), Real Time Control over Data Networks with Constrained Communication Resources

University of Illinois

1. Vikas Kawadia, MS candidate, (Completion December 2001).
2. Swetha Narayanaswamy, MS candidate, (Completion December 2001).

University of Maryland

1. B. Afsari, MS candidate.
2. M. Goldgeier, Undergraduate
3. A. Mahajan, Undergraduate
4. A. Greene, Undergraduate
5. M. Gebremichael, Undergraduate
6. P. Carlos Sodre, Undergraduate
7. T. Duong, Undergraduate
8. Adrian Cottin, Undergraduate.

3. Degrees Awarded

Boston University

1. D.J. Raghunathan, MS Degree, January 2002 Real Time Control over Data Networks with Constrained Communication Resources
2. Ying Liu, "Analysis of Regulation Mechanisms in Communication Networks", M.S. in Manufacturing Engineering, Boston University, January 2003.
3. Yong Liu, "Pricing and Resource Allocation in Communication Networks and Supply Chains", Ph.D. in Systems Engineering, Boston University, May 2002.
4. S. Vassilaras, "Measurement-based Quality of Service Provisioning in Multimedia Telecommunication Networks", Ph.D. in Electrical and Computer Engineering, Boston University, January 2002.

University of Illinois

1. Vikas Kawadia, MS Degree, (Completion December 2001), Design and Implementation of a Power Control Protocol in Ad-Hoc Networks.
2. Swetha Narayanaswamy, MS Degree, (Completion December 2001), Power Control in Ad-Hoc Wireless Networks.

Harvard University

Aleksandar Rabiner, MS Degree, June 2002.

University of Maryland

No degrees were awarded under this grant during the period January 2002 through December 31, 2002.

4. Scientific Progress

Executive Summary

This report describes the progress of a multi-university research effort to develop the technological foundations of Communicating Networked Control Systems during the period December 1, 2001 - November 30, 2002. At Boston University, the lead institution, progress is reported on five interrelated tasks: (i) new results on source coding of feedback signals in control applications involving rate-limited communications channels show that single-bit control offers optimum performance when the channel capacity is time varying; (ii) work has begun on communications and information processing strategies for coordinated control of squadrons of mobile robots; (iii) work has continued on pricing as a means to allocate bandwidth and other resources in networked control systems; (iv) new results have been obtained giving nearly optimal solutions to complex scheduling and routing problems for large-scale multiclass queuing networks; and (v) work has been started on a small-scale prototype ad hoc optical communications network. At the University of Maryland, (i) several efforts are continuing aimed at establishing the geometric foundations and information processing requirements for controlled motions of fleets of UAV's; (ii) new results on particle filters and change detection are being applied to navigation problems and congestion and admission control for data networks; (iii) new results are reported on interrupt-based loop closure for stabilizing a large family of linear systems which must be multiplexed on a shared feedback channel with limited channel capacity; work has continued on the use of channel state information (CSI) and its use in determining coding rates for reliable communication; and (iv) work has continued on optimal filtering with quantized sampling and jointly optimal quantization and control for hidden Markov models (HMM's). Work at Harvard University has also investigated the extent to which the quantized values of a Gauss Markov process allows one to reconstruct the process; also work is nearing completion and in a few months it is expected that there will be a demonstration system which uses linguistic inputs to control a highly dynamic and open loop unstable system over a wireless link. At the University of Illinois, considerable progress is reported on the problem of limited attention switching, and scheduling policies have been designed which are guaranteed to be stable.

Institutional Summaries

In the Boston University component of the research effort, progress can be reported in five areas. In the first of these, new results on source coding of feedback signals in control applications involving data-rate constrained communications channels show that single-bit control offers optimum performance when the channel capacity is time varying. The applications setting for this problem involves systems in which actuators, sensors and other components are connected via data-rate constrained links such as packet-switched wireless radios and other shared communications channels. Results have been submitted for publication which treat a model Digital Finite Communication Bandwidth (DFCB) problem where there are time-vary data-rate constraints such as might arise from intermittent network congestion and asynchronism of sampling and control actuation. Because of the possibly unpredictable fluctuation of the data rate, we are interested in feedback control designs that will tolerate significantly constrained data rates on feedback loops while providing acceptable performance when such data rate constraints are not in force. In light of a very basic notion of acceptable performance, we found that control designs with different numbers of quantization levels tolerate constrained data rates differently. This has led to the conclusion that binary control represents the appropriate control quantization under data rate constraint. The advantage margin of binary control has been investigated numerically with and without the sampling/control asynchronism being taken into account. We have also shown that the advantage margin is more substantial with asynchronism taken into account.

The Boston University group can also report preliminary results on the development of communications and information processing strategies for coordinated control of squadrons of mobile robots. Efforts to apply computer vision and various optical and acoustic proximity sensors for distributed/ coordinated motion control of a small group of autonomous vehicles has led us to consider a number natural feedback control laws which utilize realtime measurements of relative distances between the vehicles. Unfortunately, none of the feedback laws satisfies Brockett's necessary conditions for asymptotic stabilization. They *do* appear to provide a basis for practical solutions to a number of interesting vehicle control problems, however. Part of the rationale for proposing feedback laws which are not asymptotically stabilizing is that in a number of cases of practical interest, one may show that the set of initial conditions which are not driven to the prescribed rest point is either small (in some sense) or uninteresting (in the problem context) or both. In some cases, one can also show that by choosing feedback gains in terms of the problem's initial conditions—using say a table look-up—it is possible to steer from any given initial state into an arbitrarily small neighborhood of the desired goal state. The aim of the research here is to develop a large catalogue of simple controlled motions which in appropriate sequential combinations permit autonomous nonholonomic vehicles to assemble themselves and execute coordinated motions in highly structured formations.

We report progress on distributed resource allocation in Networked Control Systems (NCS). NCS will consist of an array of controllers, sensors, and actuators communicating over a communication network. These devices will serve a very diverse set of physical systems and processes, hence, they will substantially differ in bandwidth requirements, access patterns, routing, as well as, urgency and importance of the messages they generate. Our work is developing resource allocation mechanisms that respect the relative importance of various devices. In particular, during times of congestion, devices with less critical messages should reduce their load on the network to make room for the critical ones. To this end, we have employed the use of pricing signals as a way of formulating the interaction between devices and the network. More specifically, we have considered an arbitrary multiservice network with fixed routing. The network charges a fee per communication session which affects the demand for establishing sessions. We have proposed pricing strategies that aim at maximizing the total social welfare of participating devices (expressed in terms of utilities that characterize the relative importance of each device). In our resource allocation setting, prices do not need to involve a monetary exchange between network and devices. They should be viewed as feedback signals from the network to the devices, indicating the level of congestion. Our main result is that in a limiting regime of "many small devices," (i.e., with small bandwidth requirements compared to the total available capacity) laws of large numbers take effect and a simple static pricing scheme is asymptotically optimal. That is, under stationarity assumptions, prices need not be dynamically adjusted but can remain fixed. A static pricing scheme, such as the one we proposed, has obvious implementation advantages: charges evolve in a slower time-scale than congestion phenomena, and no elaborate real-time mechanism is needed to communicate prices to the various devices. Moreover, prices can be computed in large scale systems in a distributed and asynchronous manner.

We report related work on scheduling and routing in multiclass queueing networks. We have considered a very general Multiclass Queueing Network (MQNET) model and proposed a new class of scheduling and routing policies to optimize an overall system objective. In open networks the objective is to minimize weighted average delays and in closed networks to maximize weighted average throughputs. The class of MQNETs we studied is rich enough to accommodate many applications of interest to the Center's work on Communicating Networked Control Systems including: scheduling and routing of messages in ad hoc device and sensor networks, and optimizing the operation of data centers and networks of servers. Arguably, sensors and actuators in network control systems will be deployed in extremely harsh environments and will depend on bandwidth-limited wireless transmissions in potentially very noisy settings. Moreover, they may be powered by batteries, thus, energy conservation will be critical. This suggests that message exchange via the communication network should be highly optimized which is the central aim of our work in this area. Optimizing a general MQNET (in terms of scheduling and routing) is highly non-trivial; in fact, an optimal policy is likely to remain elusive as there exist strong complexity results (finding an optimal policy is EXP-complete meaning that provably no polynomial-time algorithm exists). We have developed a suboptimal class of so called target-pursuing policies that are motivated from the success of state feedback laws in control and our earlier work in characterizing the achievable region of MQNETs. We have established the stability of the proposed policies and experimented with a large number of network topologies. Our numerical results suggest that target-pursuing policies are quite close to the optimal (when computationally tractable to obtain) and substantially outperform heuristic alternatives.

An ongoing component of the research at Boston Unviersity is aimed at developing *to ad hoc freespace optical networks* technology. The work involves an advanced (Canobeam) freespace optical communications system (500MB/s) and a squadron of mobile robots with steerable mirrors which can be used to redirect laser beams. Current freespace optical communications systems use fixed transievers which are carefully aligned to assure good signal reception. The technology needed to dynamically reconfigure freespace optical communication networks will require the solution of several interrelated problems:

Figure: artoo.bu.edu is configured with IR beam detectors and a gibaled mirror system for research on freespace optical communications.

1. The beam location problem:
2. The beam pointing problem;
3. The beam tracking problem; and
4. The cooperative signal maintenance problem.

The *beam location problem* involves searching a 2-dimensional space to locate the laser beam of one of the optical communications transievers. Each transmitted beam must be located by one of the mobile robots in the group. The *beam pointing problem* requires the robot agents which have found the communication beams from the optical transievers to find each other and direct the laser beams so as to form a reliable communications channel from one transiever to the other. The *beam tracking problem* involves motion of the robot agents in which the communications channel is maintained. This is an important problem which anticipates the objective of stabilized mobile freespace optical communications which will be a large part of future phases of the research. A related problem is that of *cooperative signal maintenance*. Work on this problem is aimed at understanding the types of *side information* the robot agents require to most effectively carry out the mission of maintaining a reliable information link.

At Harvard University, the PI and his student Jian Zou have investigated the extent to which the quantized values of a Gauss Markov process allows one to reconstruct the process. This has direct relevance to the network control problem in that quantized data can be shared at various bit rates over a network and the extent to which finer quantization leads to better knowledge of the signal needs to be quantified. There are several aspects of this problem. If one adopts a continuous time model in which a signal sent each time the process in question passes through a level change then one can use a modified version of the conditional density equation to propagate the conditional density. This equation is tractable in the one dimensional case but in higher dimensions in becomes numerically intensive. We have worked with a number of approximate methods and have developed several alternatives, the effectiveness of the possibilities depend on the power spectrum of the process that is to be estimated. If one adopts a discrete time model in which the quantified signal is sampled at regular intervals with the quantified value being transmitted, then the computation of the conditional density model itself is quite complex and further work is needed to define a suitable approximation.

Working with Hongyi Li, we have further developed the idea of linguist control of dynamical systems. Our primary test bed has been a six degree of freedom pendulum system which is capable of operating in various modes. This system operates over a wireless link with the goal being that of orchestrating effective mode switching while maintaining stability. This project is nearing completion and in a few months we expect to be able to demonstrate a system which uses linguist inputs to control a highly dynamic and open loop unstable system over a wireless link.

At the University of Illinois, considerable progress was made on the problem of limited attention switching. Scheduling policies were designed which are guaranteed to be stable. It was shown that switching on the state with the largest norm is stabilizing. Joint Grant funded work by Kumar (Illinois) and Hristu (Maryland) has looked at the stabilizability of ensembles of linear systems whose feedback loops are closed via a shared network. The network can accommodate only a limited number of systems at any one time. Kumar and Hristu explored a variety of interrupt-based communication policies for deciding which system(s) should be allowed to close their feedback loops (and for how long) and derived a sufficient condition for stability. Theirs is the least conservative condition that may be placed on the eigenvalues of the systems making up the ensemble. They are currently exploring the performance of interrupt-based communication strategies in problems other than stability and in the context of ensembles whose dynamics may stochastic or nonlinear. These results are detailed in a paper by D. Hristu and P. R. Kumar at the 2002 CDC and in an upcoming submission to the *IEEE Trans. on Automatic Control*.

At the University of Maryland, In joint work, E.W. Justh and P.S. Krishnaprasad have been examining coordination of small formations of UAVs (unmanned aerial vehicles). Progress has been made in devising control laws that determine the curvature of UAV trajectories. The objective here is to achieve formation cohesion, transport to target areas, and re-shaping of formations. A key problem is the stabilization of a prescribed formation shape. This is to be achieved using inter-UAV communication. In order to be able to scale up the control schemes to large collections of UAVs, we are considering the communication among the UAVs to be based on low duty-cycle RF pulses, from which neighboring UAVs can extract crude range and direction-of-arrival information.

As a first step, we have considered an idealized model of the planar motion of a single UAV in response to a fixed beacon signal. Using Lyapunov function methods, we have studied the convergence of the UAV trajectory to a circular limit-cycle solution with the beacon at the center. The kinematic description of the control scheme is based on the planar Frenet-Serret equations, which describe the evolution of a curve with constant constant speed (corresponding to constant heading speed of the UAV) but variable curvature (corresponding to steering control applied to the UAV based on the measured beacon signal). We have also extended this analysis to an idealized planar model of a pair of UAVs, with each treating the other as its beacon.

We are now working on extending the planar analysis to larger collections of UAVs, and on examining the three-dimensional control problem. We have also begun interacting with the Naval Research Laboratory (NRL) to learn more about what types of UAV control problems are of military interest, how limitations on flight performance of actual UAVs need to be taken into account in the control laws, and how energy and payload constraints enter into the problem of coordinated control of UAV formations in a practical way.

A joint effort with NRL on a ground test-bed project is expected to take place during Spring 2003. We have also had interactions with Intelligent Automation Inc., a Maryland company involved in the use of ultra wideband communication in UAVs.

There is considerable synergy between the ideas on formation control developed with Justh and the work on control of satellites with Zhang. This arises from the common nonlinear dynamical questions addressed in both settings. Additionally, in the paper for ICRA 2003 (Zhang, Goldgeier and Krishnaprasad), methods based on shape space theory are introduced. The role of communication between formation elements is also considered.

In joint work of Babak Azimi-Sadjadi and P. S. Krishnaprasad progress has been made in the rigorous development of the theory of projection particle filters with applications to navigation and change detection. The work has been reported in multiple conference venues and journal papers are being readied for submission. Since moving to RPI as a Research Assistant Professor, Azimi-Sadjadi continues his association with Maryland as a half-time post-doc supported under the Center grant. The interactions with Maryland are continuing.

In the ongoing work of Babak Azimi-Sadjadi the problem of congestion control in computer communication networks is under study. Here, we consider a framework that uses m bits per packet to convey information about network state to users. A protocol is being developed in which routers encode state information on packets passing through them and a particle filtering mechanism at the receiving end is used to reconstruct this information. This serves as a basis for the design of congestion control algorithms with a focus on real-time applications and distributed admission control. A key issue of interest here is packet transmission delay control. The receiver of a packet informs the sender if the constraints on packet delay are unmet. The sender informs the router and rate limits are placed using the m bits per packet. Babak Azimi-Sadjadi is developing a network control testbed to support this study.

In the work of P. S. Krishnaprasad, in collaboration with Arash Komaee, Eric Justh and Prakash Narayan, problems of using freespace optical channels in feedback control are being investigated. Preliminary channel models and computations of fade statistics have been done. A key consideration of interest is to determine the relative significance of amplitude fade over phase fade. This will influence the choice of methods to estimate (and correct for) channel state. Adaptive optics is of interest in this connection. Komaee has done further work on modeling the freespace optical channel towards developing a suitable channel state estimation scheme.

In the work of P. S. Krishnaprasad, in collaboration with Bijan Afsari, Domenico Napoletani and Carlos Berenstein, problems of unscrambling mixture sensor data from multiple sources are being considered. Progress is being made in the development of algorithms for demixing in both centralized and decentralized settings. Algorithms based on higher order statistics (higher order singular value decomposition) are under investigation as well as time-frequency methods. Computational evalutions of these algorithms are under way.

Also at the University of Maryland, D. Hristu is exploring a class of path planning problems in groups of vehicles whose interactions are limited by the presence of communication constraints. He has focused on a so-called "local pursuit" algorithm that succesively optimizes the trajectories of a group, using local interactions only. It has been shown that our algorithm is useful for solving not only the kinematic path optimization problems for which it was originally designed, but also a much more general class of optimal control problems which may involve nonlinear or nonholonomic systems. The results of this effort are detailed in a paper submitted to the *IEEE Trans. of Robotics and Automation*.

Work by Narayan at the University of Maryland has focussed on reliable communication over a "downlink" wireless link. The associated mathematical model, called the "broadcast time-varying fading channel," serves as a (discrete-time) description of the downlink of a wireless channel, subject to frequency nonselective fading, with a single sender transmitting to K receivers. The single (base-station) sender or sensor transmits receiver-specific as well as common information in a broadcast mode to multiple (mobile) receivers or actuators. Varying extents of channel state information (CSI) concerning the degree of the fades experienced by the transmitted signals are provided to the transmitter and the receivers. The current emphasis has been on studying the improvements in rate-performance as a function of CSI.

The main objective has been to determine the "information capacity region," i.e., the set of all coding rates at which information can be reliably transmitted over the channel with low message decoding error probabilities. This analysis is then being used to identify appropriate performance metrics, e.g., reliable channel "throughput" which will serve as a quantitative basis for the assessment of different transmitter power control strategies, i.e., the adaptation of transmission power as a function of transmitter CSI.

In an attempt to understand the mathematical structure of the general problem, our recent work has focussed on the following three specific channel models which constitute simplified and extreme cases of realistic situations. Nonetheless they pose technical challenges which, if fully understood and resolved, would help provide useful answers in other situations as well.

> Model 1: The sender and receivers have full CSI i.e., complete knowledge of the fades experienced by all the receivers;
> Model 2: The sender has no CSI, while the receivers have full CSI.
> Model 3: The sender has full CSI; each receiver has complete knowledge of its own fade together with a comparative ranking of its fade with respect to the fades of the other receivers.

While a solution for Model 1 has existed in the prior literature, our solution involves a new power allocation technique in the "converse proof" of possibly wider applicability. In particular, this approach, and modifications thereof, are now being tried for Models 2 and 3.

Another part of the University of Maryland effort has been focused on *Hierarchical, distributed dynamic programming and Q-learning.* The work has yielded new results on hierarchical dynamic programming, computational complexity reduction using state aggregation, distributed hierarchical dynamic programming and distributed hierarchical Q-learning.
Principal investigator John Baras and his students have investigated the DCA (Direct Computation based on the Aggregation) scheme. The DCA scheme computes the sub-optimal policy and approximate cost-to-go values for the original system. One of the most important concerns is how to reduce the aggregation error. The critical factor that decides the aggregation error is the sampling probability. They have investigated methods for selecting sample states properly within a cluster to minimize the aggregation error, they have obtained the following results: (a) For a system partitioned according to strong and weak interactions, selecting sampling states according to the steady probability distribution under a given policy is shown to give approximately the mean cost-to-go value of states in each cluster; (b) When all the states in the system are aggregated into a single cluster, then under a given stationary policy, the cost-to-go value of the macro-state can be obtained directly and it is equal to the mean cost-to-go value of the states in the original system. Another important factor that affects the aggregation error is the partition structure. The initial partition of the

system may not be “optimal”. The team hasdeveloped an adaptive aggregation algorithm to adaptively aggregate states according to current estimates of cost-to-go values of the states. States with approximately equal cost-to-go values are grouped into the same cluster, and they have also analyzed the computational complexity of the aggregation algorithms.

Distributed computation of a large scale Markov Decision Process (MDP) reduces computational time due to parallelism of computation. Despite the advantages of Distributed Dynamic Programming (DDP), there is a major obstacle that limits its application in real world problems: the information exchange required for a large system can be prohibitive. In a system that has very limited channel capacity, application of the DDP becomes impractical or very expensive. The Baras group has developed a new Distributed Hierarchical Dynamic Programming (DHDP) algorithm, where the original system is divided into K subsystems and the computation is carried on in each subsystem in parallel. The amount of data transmitted from a subsystem to a neighboring subsystem in the communication channel is limited to only one unit, which is independent of the size of the subsystems. This minimum information exchange between subsystems has significant practical meaning for systems with very limited channel capacities. They have proved the convergence of the DHDP and obtained its error analysis. They have also obtained comparisons with other type of DDP algorithms which showed that the new algorithm has significant advantages. There are also results on how to select sample states.

State aggregation algorithms usually require that states in each cluster can take different actions. New results show that for an ε-homogeneous partition, the states within the same cluster can take the same action without causing large errors. Explicit error bounds were derived. Therefore, the number of macro-actions to be evaluated at each cluster is reduced from $|S_k|^{\Psi}$ to only Ψ, where $|S_k|$ is the number of states in cluster S_k and Ψ is the size of the control space of a real state. An ε-homogeneous partition is defined on systems whose states have the same control space. There is further extension of the results to systems whose states may have different control spaces. The Baras group has derived an error bound of applying the DCA scheme over the simplified control space. However, it may be expensive to obtain an ε-homogeneous partition. Therefore, we have proposed another approach to simplify the control space by the use of pseudo-residual errors. It has been demonstrated that it is easy to compute the pseudo residual errors and find the corresponding partition.

Q-learning itself is a model-free reinforcement learning method. The team has developed a Distributed Hierarchical Q-learning (DHQ) algorithm for large-scale model-free systems, where the original system with an unknown model is divided into K subsystems and the computation is carried on in each subsystem in parallel. The data transmitted from a subsystem to a neighboring subsystem in the communication channel is only the cost-to-go value of the subsystem, which is independent of the size of the subsystems. The minimum information exchange between subsystems has significant practical meaning for systems with very limited channel capacities. It has been proved that the convergence of the DHQ and obtained its error analysis. Most importantly, by using the hierarchical structure, there is an explicit error bound for Q-learning based on state aggregation.

Another part of the research at the University of Maryland has dealt with *jointly optimal quantization and filtering for Hidden Markov Models (HMM).* The team has formulated the jointly optimal quantization and filtering problem for a HMM, in general (i.e. without special and restrictive assumptions). The output of the HMM is quantized (coded) and sent over a communication link. The receiver then recursively estimates the state of the HMM based on the received information. We seek the optimal coding (quantization) scheme to minimize a cost function that takes into account the estimation error, the communication requirement, and the delay. The coding scheme is in general varying in time and the block length is also variable. There is the further requirement that the coding scheme at any time be determined only by the information available to the receiver up to that moment. The work has shown that the problem can be recast as a stochastic control problem, where the information state is the conditional probability of the state given the transmitted information. The results give explicitly the recursive formula for the information state. The value function satisfies a special type of Dynamic Programming (DP) equation.

The team has also investigated numerical solution of the DP equation. A quantization scheme for a discrete set is essentially a disjoint-grouping scheme for the elements of the set. Due to the combinatorial nature of the problem, the complexity of finding the optimal scheme grows up quickly with the cardinality of the set. The effort has provided a tree-structured algorithm and other methods to eliminate repetitions in enumeration of grouping schemes that have resulted in speeding up the computations. By varying the weights associated with different cost terms, one obtains a family of optimal policies. These may then be applied to output samples generated through HMM simulation. It was shown that by changing the cost weights, one can obtain different Pareto-optimal quantization schemes.

Jointly optimal quantization and control for HMM. The work has extended the previous framework to the setting of jointly optimal quantization and control. The cost function consists of a term related to the system performance and a term related to the communication cost. In particular, we have analytically solved a two-state, two-output, two-control problem in detail. The value function is shown to be piecewise linear and concave. The tradeoff between the two competing goals is revealed through the Pareto-optimal curve. Ongoing work involves extension to the case where quantization of control (thus communication cost relating to control signal) is also considered.

Continuous filtering and smoothing with quantized observations. It has been recognized that due to the possibility of the Girsanov transformation, it suffices to solve the problems of filtering/smoothing/prediction based on quantized observations of the standard Brownian motion. For standard Brownian motion, because of the strong Markov property (times when the quantized output levels change are stopping times), to estimate the value of the actual trajectory at any time, it is sufficient to use the times and levels corresponding to the immediately previous and next changes in the quantized output. In fact, the motion in this time interval becomes a restriction of the `Brownian bridge' - note that this process is no longer Gaussian! For estimates like the least square estimate of the trajectory, there are symmetry reasons that restrict the possible forms of the estimate function to be simple. Current work involves explicitly calculating such estimates.

Decentralized control of autonomous vehicles. As part of the research effort, the team has investigated the problem of cooperative control of autonomous vehicles (called agents). The mission of the agents is to maneuver themselves to cover a target area. They are also expected to maintain good area coverage at any time and avoid obstacles, collisions and dangerous regions. Considering the communication constraints, we explore a decentralized approach for path generation. Each agent makes its moving decision based only on local information and/or static information (such as the target position). This is accomplished by minimizing a cost function encoding information about the nearest neighbors, obstacles, static and dynamic threats, and the target. Simulations of the resulting schemes based on Matlab have been conducted. We observe interesting emergent behaviors of the agents by changing the weights associated with different cost terms. We have also formulated the entire problem in the framework of dynamic, adaptive and interacting potential functions.

There are also some analytical results relating to emergent behaviors. In particular, the group analyzed the existence and stability of equilibrium after agents enter the target area, and the conditions for an agent to evade a moving threat and enter the target area.

Dynamic clustering and swarm intelligence. The research also continued the investigation of deterministic annealing, stochastic annealing and swarm intelligence based algorithms as useful means for abstracting various types of distributed asynchronous algorithms for solving the multi-criterion problem that results from our formulation of distributed asynchronous control under communication (or other resource) constraints. Research has continued on dynamic clustering in networked control systems, and in particular the team initiated the investigation of performance evaluation of dynamic clustering schemes, via performance measures that have practical significance such as: frequency of clustering and re-clustering (lower the better), stability of clusters, speed of recovery when a node joins, a node leaves recovery, a link goes down, various parameters associated with clusters like size (No. of members) and diameter (in terms of delay or hops), and last but not least control goal achievement or control performance.

Research in this area must deal with various degrees of uncertainty in mobile networked control systems. Dynamic distributed adaptive control cannot be based on state information or even state estimation and filtering; since the mobility and dynamic nature of these networked systems will prohibit timely updates of local and global "networked system" states. The research aims to develop several types of algorithms for distributed and asynchronous control with degree of adaptation tuned to the network clusters. A promising framework for integrating the various types of dynamic adaptive distributed control algorithms needed is that of gradient systems or locally interacting systems. These foundations lead to new distributed control algorithms which computationally are within the "emergent computation" class of algorithms. This representation allows a framework for a combined analytical, numerical, simulation based performance evaluation, which has been lacking todate. Performance evaluation is lacking at a systematic and rigorous level, and typically consists of single case limited simulation studies. This lack of "basic principles" and a combined analytical-numerical-simulation methodology for evaluating and designing dynamic distributed control schemes for mobile networked control systems, coupled with the non-existence of a large real-life testbed, has severely limited the development of control algorithms with proven performance, and the understanding of the role of various parameters and related sensitivities. For example scalability of algorithms cannot be evaluated. The work will address this challenge by investigating algorithms of the "Swarm Intelligence" type, for two reasons: (a) as a useful abstraction of several distributed and asynchronous control algorithms; (b) as a means for discovering new high performance distributed control algorithms for specific applications.

This research has led us to new algorithms, and new methods for performance evaluation. In the context of investigating analytically the performance of swarm based optimization algorithms, Baras's team has established preliminary analytical connections between simulated annealing and swarm intelligence methods. They have obtained formulations of various swarm intelligence based algorithms for distributed control as a reinforcement learning scheme, and more specifically as a stochastic approximation scheme.

5. Technology Transfer

Personnel from the Center for Communicating Networked Control Systems have continued interacting with researchers from Telcordia, Johns Hopkins, BBN, and FCS, in an effort to further develop the application of our dynamic clustering methods using value-function non-variation in autoconfiguration and routing. Several new metrics have been identified. An innovative scheme has been co-developed by Center personnel and Telcordia as a result of these efforts under the CTA on C&N program that we are also participating. This scheme was implemented and resulted in the first ever demonstration of a gateway router in heterogeneous routing for mobile adhoc networks (MANET).

After several meetings with ARL personnel who are leading the FCS program, in an effort to understand and characterize mobility patterns of future Objective Force and FCS systems, we have adopted a more appropriate mobility description which utilizes trajectories for each node in the network of control systems according to their mission and capabilities as they fit the battle or military mission. We have identified sources of such mobility patterns and have used them in evaluating our research results in distributed and asynchronous control under communication constraints.

These adjustments have been incorporated in the formulation of swarm intelligence based coordination algorithms and in the problem involving the coordination, collaboratively and in a distributed and asynchronous manner, of a set of mobile vehicles equipped with sensors and communications towards achieving a specific goal described in terms of geographic advancement and territory control. This problem was used as a test (via simulations) of our theoretical results in distributed asynchronous control under communication constraints. Results will be transferred to the ARL and the FCS program.

Discussions with Dr. Jeff Heyer and Dr. Ted Roberts of NRL have also taken place to explore collaborative research in control based on novel communication links between unmanned aerial vehicles. Specific technological characteristics of current DOD vehicles are under discussion in guiding this research.

A course in approximate nonlinear filtering ECSE-6965 has been designed and taught during Fall 2002 at Rensselaer Polytechnic Institute, by Babak Azimi-Sadjadi.

At the 2002 IEEE Conference on Decision and Control (Las Vegas, December 10-13, 2002), three of the Center principals (Baillieul, Brockett, and Krishnaprasad) organized two sessions of invited presentations by leading researchers in the field. The session titles and contents were:

A. *Feedback Control over Networks* (Wednesday, December 11, 2002)

1. Guofei Jiang and George Cybenko "Query Routing Optimization in Sensor Communication Networks"
2. Wing Shing Wong, "Fairness Issues in Peer-to-Peer Networks"
3. Karl Johan Astrom and Bo Bernhardsson, "Comparison of Periodic and Event Based Sampling for First-order Stochastic Systems"
4. Yong Liu and Weibo Gong, "Challenges to Congestion Control Posed by Concurrent Downloads"
5. I.C. Paschalidis and Y. Liu, "Distributed Resource Allocation in Multiservice Communication Networks Using Pricing"

6. P.S. Krishnaprasad, “Control over a Freespace Optical Channel”

B. *Convergence of Communication and Control* (Thursday, December 12, 2002)

1. Liang-Liang Xie and P. R. Kumar, “New Results in Network Information Theory: Scaling Laws and Optimal Operational Modes for Wireless Networks”
2. Rahul Jain, Tunc Simsek, and Pravin Varaiya, “Control Under Communication Constraints”
3. Pamela Ann Abshire, “Energy cost and robustness of gain control using noisy physical channels”
4. Hristu-Varsekelis and P.R. Kumar, “Interrupt-based feedback control over a shared communications medium”
5. R.W. Brockett, “Controlling Complex Systems: Greedy vs. Fair; Speedy vs. Accurate”
6. J. Baillieul, “Feedback Coding for Information-based Control”

Other Center Technology Transfer:

J.S. Baras, “Dynamic Adaptive Routing in MANETs: New Algorithms Using Swarm Intelligence”, Distinguished Lecture in the Collaborative Technology Alliance on Communications and Networking distinguished lecture series, Army Research Laboratory, Adelphi, Maryland, July 25, 2002.

6. Patents

There were no Center patents during the reporting period.

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