

REPORT DOCUMENTATION PAGE

Form Approved

OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE

3. January 2004

3. REPORT TYPE AND DATES COVERED

FINAL REPORT May 1997-August 2003

4. TITLE AND SUBTITLE

The Design and Control of Smart Structures

5. FUNDING NUMBERS

DAAG 55 97 1 0114

6. AUTHOR(S)

Roger W. Brockett, P.S. Krishnaprasad, John Baillieul

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

Harvard University, Office for Sponsored Research

Holyoke Center, Fourth Floor

1350 Massachusetts Ave

Cambridge, MA 02138

8. PERFORMING ORGANIZATION

Harvard niversity

REPORT NUMBER 37252 MA MUR

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

U. S. Army Research Office

P.O. Box 12211

Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING

AGENCY REPORT NUMBER

37252-CI-MUR 017

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20040218 068

12 a. DISTRIBUTION / AVAILABILITY STATEMENT		12 b. DISTRIBUTION CODE	
Approved for public release; distribution unlimited.			
13. ABSTRACT (Maximum 200 words)			
<p>This is the final report of the Boston University, Harvard University and University of Maryland MURI on Design and Control of Smart Structures. The report contains a summary of results obtained from the inception of the program in May 1997 until its conclusion in August, 2003. Over this period the researchers involved produced new and useful results in the areas of micromechanical devices (fabricated and used at ARL), micro fluidics, work on the control of boundary layer flows, work on modeling micromagnetics, and a range of patented devices including a 1024 segment controllable MEMS mirror and a novel 1000 Hz optical switch based on the control of a fluid interface. More than 60 students at undergraduate, graduate and postdoctoral levels were supported under this project and over 160 papers have appeared acknowledging support from the grant.</p>			
14. SUBJECT TERMS MEMS mirrors, GPS systems, sensor and actuators in smart structures		15. NUMBER OF PAGES 22	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

Table of Contents

Statement of Problem Studied.....	1
Summary of the Most Important Results.....	1
List of Manuscripts and Journal References.....	4
Personnel.....	18
Inventions.....	20

Statement of Problem Studied

For the purposes of this MURI "Smart Structures" may be thought of as solutions to technological problems that use the controllability of physical effects such as magnetostriction, electrostriction, piezoelectric effects, and electro-osmosis to achieve their function. This represents an emerging area of engineering made possible by new developments in material science, micro fabrication and the availability of analog and digital electronic modules capable of generating the precise high frequency waveforms necessary to take advantage of such effects. The problems studied include fundamental questions on the modeling of magnetic materials operating in unusual modes, the development of new fabrication techniques for MEMS devices that can take advantage of smart materials and smart controls, modeling magnetic hysteresis in materials such as terfenol, new techniques in the control of fluids, development of larger and more capable arrays of MEMS mirrors, and new developments in NMR pulse design.

Summary of the Most Important Results

The goal of the research done under the support of this MURI is to advance the state of the art in the active control of materials and structures. We organize the summary of our results around topics according to the sub headings appearing below.

Micro fluidics: Progress on the development of theory and experiment in the area of small fluidic systems has included control of boundary layer flow, work on the control of position of fluid interfaces and peristaltically driven channel flows. Applications of the former in the area of optical switching have been developed whereas applications of latter have been made in micro mixing. We have built and analyzed an optical switch capable of switching a light beam at up to 1000 Hz by using the electrostatic deflection of a conductive/dielectric fluid interface approximately .025 inches in diameter and .01 inches deep. Optimal control principles played an important role in improving the switching speed. Because an important part of many systems being developed for micro analysis and processing is mixing in low Reynolds number flows we developed new analysis methods for understanding such mixing processes. This has been reported in the literature and is being further explored in collaboration with other groups at Harvard. New scaling laws have been developed for investigating laminar flow patterning in small scale structures. We have given a proof of concept of liquid-liquid interface spatial light modulator, We have given an analysis of dispersion in nonuniform flows in a parameter region appropriate to the investigation of mixing at small scale. This is important for chemical analysis techniques, combustion and a number of other micro fluidic applications. Electro-osmotically driven flow due to surface inhomogeneities (w/ Ajdari, Long) high-frequency peristaltic flow in a closed cavity - applications to mixing (w/ Selverov) micro-pump/motor (w/ Day) dispersion in radial flow and spatially varying configurations (w/ Brenner and Selverov)) syringe-driven flow (w/ Katopodes, Davis)

In addition there have been experiments on the development of vortex models in support of work on active flow control as well as wide ranging experiments on controlling boundary fluid flows using arrays of microjet actuators including the first detailed parametric study of optimal jet patterning for optimal control of stall due to high

angles of attack in airfoils. The vortex models capture the many results from flow-control experiments. The experimental component is detailed in the Boston University thesis of S.H. Lee and the vortex modeling appears in several papers by A.C. Smith and J. Baillieul. Considerable effort was made during the period of performance of the grant to interact with and transition results to researchers in other groups interested in these problems. In addition to technical presentations at conferences, Wright-Patterson AFB, and the United Technologies Research Center, and Boston University, in partnership with the United Technologies research Center sponsored an international workshop on The Control of Flow Separation, at the center in October of 1999.

Modeling micromagnetics: We have developed new low-order mathematical models of hysteresis nonlinearity. These can be used in the selection of materials for the control surfaces of aircraft, rotorcraft and submersibles. The refined dissipation models applicable to magnetostrictive elements are of importance for numerical simulation. These are expected to lead to new software tools for the design of actuators. The models we have developed for magnetoelastic systems, based on the Landau-Lifshitz-Gilbert equations can be used to obtain predictions of hysteresis curves. These are key to predicting the efficiency of devices. Cayley transform methods have been developed to produce accurate algorithms for micromagnetics, with projected applications in magnetostrictive actuator modeling. These methods have been tested in small size grids. This work was presented at workshops in magnetics (George Washington University, May 2001 and Princeton University, June 2001).

Work on modeling and control of hysteresis using Preisach models has led to the successful demonstrations of inversion of hysteresis in magnetostrictive actuator control. New methods based on finite automaton models of hysteresis has been developed together with a robust control theory for systems with hysteresis. (See thesis of Xiaobo Tan, jointly supervised by J. S. Baras and P. S. Krishnaprasad), In the joint work of X. Tan, J. S. Baras and P. S. Krishnaprasad, new infinite dimensional models of dynamic hysteresis have been investigated and control algorithms have been developed for tracking smart actuators with hysteretic behavior. These algorithms have been successfully tested and validated in the laboratory.

Adaptive Optics: High-resolution laser-wavefront modulation addresses a critical military need in a system that also offers near-term promise in the commercial sector. Prototype micromirror arrays with 25 or 100 pixels that have been fabricated at BU's Photonics Center have been incorporated into test beds for laser communication and/or adaptive wavefront control at Army Research laboratories (2), Lawrence Livermore National Laboratories (3), Lockheed Martin Missile Systems, NASA's Jet Propulsion Laboratory, The University of Victoria, Imperial College, the Rochester Visual Sciences Center, the Schepens Eye Research Institute, and Adaptive Optics Associates Corporation. The MURI/ARL collaboration benefits from strong and long-standing synergy between the ARL's Intelligent Optics Laboratory and Boston University's Precision Optics Laboratory. This work together has produced eight collaborative papers in archival journals and conference proceedings, and has resulted in four specially-organized technical conference sessions at annual meetings of the Society of Photo-optical Instrumentation Engineers (SPIE) on the topic of high resolution wavefront control. This collaboration, supported by the ARL Cooperative Research Program, has resulted in the following milestones:

1. The fastest adaptive optics control loop ever demonstrated (11kHz)
2. The first real-time adaptive optical imaging system to improve resolution using MEMS
3. The first demonstration of a laser-communication link using real-time adaptive compensation and a MEMS mirror
4. A comprehensive analysis of the optoelectromechanical performance of MEMS DMs in adaptive control systems, which appeared in Applied Optics (2001).

We have developed new techniques for high resolution optical phase distortion suppression, correcting for the effects of atmospheric turbulence on laser beams. This work is in collaboration with Dr. Mikhail Vorontsov of ARL and testing has been done both at ARL and at Boston University. Proof-of-concept experimental demonstration of the liquid crystal light valve (LCLV)-based high resolution wave-front control system (nonlinear Zernike filter realization) Simulation results show effectiveness against atmospheric turbulence Global nonlinear stability analysis for the continuous system model of the wave-front control system Patent disclosure (PS-2001-078) jointly to University of Maryland and Army Research Laboratory: Wave-front phase sensors based on optically or electrically controlled phase spatial light modulators for wave-front sensing and control (M.A. Vorontsov, E. W. Justh, L. Beresnev, P. S. Krishnaprasad, J. Ricklin). In joint work with Eric Justh, and in collaboration with Dr. Mikhail Vorontsov and colleagues at the Army Research Laboratory, significant progress has been made in other areas of adaptive optics as well

MEMS Fabrication: Rapid progress has been made in the design of MEMS mirrors, and MEMS arrays of silicon-based microvalves as well as in the design and fabrication of arrays of silicon-based MEMS piston actuators for applications in adaptive optics using deformable mirrors. The project capitalizes on a proven and highly successful collaboration between researchers at the Boston University Photonics Center and researchers at the Army Research Laboratory. One project involves an optical system consisting of a BU 324 element silicon spatial light modulator embedded into an optical free-space laser communication link to allow high speed control of the wavefront phase. This system is being used in research concerning compensation of path aberrations and enhancement of security in point-to-point data links.

Much of the micromirror technology developed through this project has been licensed by Boston University for production by Boston Micromachines Corporation (BMC). Commercial sales of this pilot product in the past two years have exceeded \$400K. In a recent collaboration supported by DARPA, the Boston University/BMC team has fabricated next-generation device with 1024 mirror pixels and improved optical quality. The military impact of micromirrors produced through the MURI research is measurable in terms of superior targeting capability for laser-guided ordinance, and improved stealth in photonic point-to-point communications. The commercial impact will be felt in laser communications and biomedical instrumentation for retinal imaging.

Control Architectures: Based on earlier work by Harvard colleagues, the Boston University group established the first statement of what has become known as the Data-rate theorem, placing bounds on the minimum data rate required to stabilize a system.. The design of methods for optimizing communication patterns appropriate for controlling arrays, and the data-rate theorem mentioned were announced in a paper and presentation given at an ARO workshop on smart structures at the Pennsylvania State University, in August 1999. This work has led to ongoing developments in communications and control which is being pursued with support of the

Communicating

Networked Control. The BU/ARL collaboration, supported by the ARL Cooperative Research Program, has resulted in the following milestones: The fastest adaptive optics control loop ever demonstrated (11kHz), The first real-time adaptive optical imaging system to improve resolution using a MEMS link with real-time adaptive compensation and a MEMS mirror and a comprehensive analysis of the optoelectromechanical performance of MEMS digital mirror in adaptive control systems. (Applied Optics (2001)

List of Manuscripts and Journal References

Harvard University:

Papers Published in Peer Reviewed Journals

R. Brockett and N. Khaneja, "*On the Stochastic Control of Quantum Ensembles,*" in System Theory Modeling, Analysis, and Control, (T. Djaferis and I. Schick, eds.) Kluwer Academic Press, Norwell, MA, pp. 75-96, 1999,.

R. Brockett and D. Liberzon, "*Nonlinear Feedback Systems Perturbed by Noise: Steady-State Probability Distributions and Optimal Control,*" Transactions on Automatic Control, vol. 45 n. 6, pp. 1116-1130(2000)

R. Brockett and D. Liberzon, "*Quantized feedback stabilization of linear systems,*" IEEE Transactions on Automatic Control, vol. 45 n. 7 pp. 1279-1289 (2000)

N. Khaneja, R. Brockett and S. Glasser, "*Time Optimal Control of Spin Systems,*" Physical Review A, vol. 163, March, 2001.

N. Khaneja, R. Brockett and S. Glasser, "*Sub-Riemannian Geometry and Time Optimal Control of Three Spin Systems: Quantum Gates and Coherence Transfer,*" Physical Review A, 02302, vol. 65, (2002)

D. Hristu and R. Brockett , "*Experimenting with Hybrid Control,*" IEEE Control Systems Magazine, vol 22, No. 1, pp. 82-95. 2002

N. Twum-Danso, and R. Brockett, "*Trajectory Estimation from Place Cell Data,*" Neural Networks, vol. 14 (2001), pp. 835-844.

M. Egerstedt and R. Brockett, "*Feedback can Reduce the Specification Complexity of Motor Programs,*" IEEE Transactions on Automatic Control, vol 48, Feb 2003

D. Long, H.A. Stone, and A. Ajdari,1999, "*Electroosmotic flows created by surface defects in capillary electrophoresis,*" J. Coll. and Int. Sci. 212, 338--349.

R.F. Day and H.A. Stone, "*Lubrication analysis and boundary integral simulations of a viscous micropump*," J. Fluid Mech. 416, 197-216.

F.V. Katopodes, A.M.J. Davis, and H.A. Stone, "*Piston flow in a two-dimensional channel*," Phys. Fluids 12, 1240-1243.

R.F. Ismagilov et al., "*Experimental and theoretical scaling laws for transverse diffusive broadening in two-phase laminar flows in microchannels*," Appl. Phys. Lett. 76, 2376-2378.

M.Z. Bazant and H.A. Stone, "*Asymptotic analysis of reaction-diffusion fronts with one static and one diffusing reactant*," Physica D

S.A. Koehler and T.R. Powers, "*2000 Twirling elastica: Kinks, viscous drag, and torsional stress*," Phys. Rev. Lett.

L.E. Becker, S.A. Koehler and H.A. Stone, "*On self-propulsion of micro-machines at Low Reynolds Number: Purcell's three-linkswimmer*". Journal of Fluid Mechanics 490, 15 (2003)

H.A. Stone, "*Philip Saffman and viscous flow theory*," J. Fluid Mechanics vol. 409, 1 65--183, 2000.

R.F. Ismagilov, A.D. Stroock, P.J.A. Kenis, H.A. Stone, and G.M. Whitesides, "*Experimental and theoretical scaling laws for transverse diffusive broadening in two phase laminar flow in microchannels*," Appl. Phys. Lett. vol 76, 2376--2378, 2000.

T. Katopodes, A.M.J Davis, and H.A. Stone, "*Piston flow in a two-dimensional channel*," Physics Fluids vol. 12, 1240--1243, 2000

M.Z. Bazant and H.A. Stone, "*Asymptotics of reaction-diffusion fronts with one static and one diffusing reactant*," Physica D, vol. 147, 95-121, 2000

R.F. Day and H.A. Stone, "*Lubrication analysis and boundary integral simulations of a viscous micropump*," J. Fluid Mechanics, vol. 416, 197--216., 2000

B.A. Grzybowski, H.A. Stone, and G.M. Whitesides, "*Dynamic self-assembly of magnetized, millimeter-sized objects rotating at the liquid-air interface*," Nature, vol. 405, 1033-1036., 2000

K. Selverov and H. Stone, 2001
"*Peristaltically driven channel flows with applications toward micro-mixing*," Phys. Fluids. Phys. Fluids 13, H. McKinley & H.A. Stone).

Papers Published in non-Peer Reviewed Journals or Conference Proceedings

R. Brockett, "*Minimum Attention Control*" Proceedings of the 1997 CDC, 1997

- R. Brockett, "*Singular Values and Least Squares Matching*" Proceedings of the 1997 CDC, 1997.
- R. Brockett, "*A Rational Flow for the Toda Lattice Equations*," in *Operators, Systems and Linear Algebra*, (U. Helmke et al. eds), B.G. Teubner, Stuttgart, 1997, pp. 33-44.
- R. Brockett and K. Morgansen, "*Nonholonomic Control Based on Approximate Inversion*," Proc. of the 1999 American Control Conference, San Diego CA, 1999, pp. 3515-3519.
- R. Brockett, "*Stationary Covariance Realization with a Specified Distribution of Amplitudes*," Proceedings of the 1998 Conference on Decision and Control, Tampa, FL, 1998, pp 3742-3745.
- R. Brockett, "*Control of Stochastic Ensembles*," Astrom Symposium on Control, (B. Wittenmark, A. Rantzer, eds) Studentlitteratur, Lund Sweden, 1999 pps. 199-216.
- R. Brockett, "*Explicitly Solvabontrol Problems with Nonholonomic Constraints*," Proc. of the 1999 CDC Conference, Phoenix AZ, 1999, pp. 13-16.
- R. Brockett, W. Gong and Y. Guo, "*Stochastic Analysis for Fluid Queuing Systems*," Proc. of the 1999 CDC Conference, Phoenix AZ, 1999, pp 3077-3082.
- R. Brockett and N. Khaneja, "*Dynamic Feedback Stabilization of Nonholonomic Systems*," Proc. of the 1999 CDC Conference, Phoenix AZ, 1999, pp 1640-1645.
- M. Egerstedt, P. Ogren, O. Shakernia, and J. Lygeros, "*Toward Optimal Control of Switched Linear Systems*," IEEE Conference on Decision and Control, Sydney, Australia, Dec. 2000.
- R. Brockett, "*New Issues in the Mathematics of Control*," in *Mathematics Unlimited-2001 and Beyond*, (W. Schmitt et al. Eds.) pp. 189-219, Springer-Verlag, 2001.
- N. Khaneja, R. Brockett, and Steffan Glasser, "*Optimal Pulse Design for NMR System Identification*," Proceedings of the IEEE Conference on Decision and Control, (2001)
- K.P Selverov, and H.A. Stone "*Peristaltically driven flows for micro-mixers*," Proc. of IMECE Meeting (ASME), Anaheim, November 1998, pp. 85-88.
- R.F. Day, and H.A. Stone, "*Lubrication analysis and boundary integral simulations of a viscous micropump*," MSM99, pp. 514-517, 1999.
- H.A. Stone, J. R. Lister, M. P. Brenner, "*Conically shaped drops in electric fields*," Proc. Roy. Soc. Lond. 455, 329--347. 1999
- H.A. Stone, and H. Brenner, 1999, "*Dispersion in flows with streamwise variations of mean velocity*," I and EC Research, 38, 851--854.
- A. Ajdari, and H.A. Stone "*A note on swimming using internally generated traveling waves*," 1999

Phys. Fluids. 11, 1275--1277.

H.A. Stone, "Philip Saffman and viscous flow theory," J. Fluid Mech. 409, 165-183.

Stone, H. & Kim, S., 2001 "Microfluidics: Basic Issues, Applications, and Challenges," AIChE J. 47, 1250-1254.

R.F. Ismagilov, D. Rosmarin, P. Kenis, D. Chiu, W. Zhang, H. Stone & G. Whitesides, 2001 *Pressure-driven laminar flow in tangential microchannels: An elastomeric microfluidic switch.* Anal. Chem. 73, 4682-4687.

University of Maryland

Papers Published in Peer Reviewed Journals

P. S. Krishnaprasad and D. Tsakiris, "Oscillations, $SE(2)$ -Snakes and Motion Control: A Study of the Roller Racer", (2001), Dynamics and Stability of Systems, 16(4): 347-397

V. Manikonda and P. S. Krishnaprasad (2002), "Controllability of a class of underactuated mechanical systems with symmetry," Automatica, 38(11):1837-1850.

M. A. Vorontsov, E. W. Justh and L. A. Beresnev (2001), "Adaptive optics with advanced phase-contrast techniques: part I. High-resolution wavefront sensing," J. Opt. Soc. Am. A, 18(6):1289-1299.

E. Justh and P. S. Krishnaprasad, "Pattern-forming systems for control of large arrays of actuators," Journal of Nonlinear Science 11 (2001) 239-277.

P. S. Krishnaprasad and X. Tan, "Cayley transforms in micromagnetics," Physica B 306 (2001) 195-199.

B. Azimi-Sadjadi and P. S. Krishnaprasad, "Approximate nonlinear filtering and its application in navigation", provisionally accepted for publication in Automatica, revised version submitted in August 2003.

A. Handzel and P. S. Krishnaprasad, "Biomimetic sound source localization", IEEE Sensors Journal, 2(6):607-616.

S. C. Yip and S. Antman, "Physically Unacceptable Viscous Stresses." Zeitschrift für Angewandte Mathematik und Physik, 49 (1998), 980--988.

H. Koch, and S. Antman, "Stability and Hopf Bifurcation for Fully Nonlinear Parabolic-Hyperbolic

Equations, ” Siam Journal of Mathematical Analysis 32, 2001, 360-384

S. Antman, “*Feedback Linearization and Semilinearization for Smart Elastic Structures*,” 15 pp., Journal of Elasticity 59, 2000 pp. 115-130

S. Antman and F. Schuricht, “*Incompressibility in Rod and Shell Theories*,” Mathematical Modelling and Numerical Analysis, 33, 1999, 289-304

S. Antman, “*Synthesis of Nonlinear Constitutive Functions. Applications to the Electromagnetic Control of Snapping*,” Journal of Applied Mechanics, 66, 1999, pp 280-283

S. Antman and H. Koch, *Self-Sustained Oscillations of Nonlinearly Viscoelastic Layers*, SIAM Journal of Applied Mathematics, 60, 2000, pp 1357-1387

S. Antman, “*Feedback Linearization and Semilinearization for Smart Elastic Structures*,” Journal of Elasticity v.59 (2000), 115--130.

S. Antman and H. Koch, “*Self-Sustained Oscillations of Nonlinearly Viscoelastic Layers*,” SIAM Journal of Applied Mathematics, v 60, (2000), 1357--1387.

H. Koch & S. Antman, “*Stability and Hopf Bifurcation for Fully Nonlinear Parabolic-Hyperbolic Equations*,” SIAM J. Math. Anal., 32 (2001), 360--384.

J. Wilber, & S. Antman, “*Global Attractors for a Degenerate Partial Differential Equation from Nonlinear Viscoelasticity*,” Physica D, 150 (2001) 179--208.

Antman, S., & Ting T. C. T., “*Anisotropy Consistent with Spherical Symmetry in Continuum Mechanics*,” J. Elasticity, 62 (2001), 85--93.

D. Lott, S. Antman, & W. Szymczak, W., “*The Quasilinear Wave Equation for Antiplane Shearing of Nonlinearly Elastic Bodies*,” J. Comp. Phys., 171, (2001) 201--226.

S-C. Yip, S. Antman, & M. Wiegner, “*The Motion of a Particle on a Light Viscoelastic Bar: Asymptotic Analysis of the Quasilinear Parabolic-Hyperbolic Equation*,” J. Math. Pures Appl., in press, 38 pp, 2001

S. Antman, & L. Srubshchik, “*Asymptotic Analysis of the Eversion of Nonlinearly Elastic Shells, II. Incompressible Shells*.” J. Elasticity, in press, 52 pp. 2001

S. Antman, & T. Seidman, “*Parabolic-Hyperbolic Systems Governing the Spatial Motion of Nonlinearly Viscoelastic Rods*,” 48 pp., nearly ready for submission. 2001

S. Antman, and M. Wiegner, *The Motion of a particle on a light viscoelastic bar: Asymptotic analysis of the quasilinear parabolic-hyperbolic equation*, J

ournal de Mathematiques Pures et Appliques, 81, 2002, 283--309.

Papers Published in non-Peer Reviewed Journals or Conference Proceedings

R. Venkataraman and P. S. Krishnaprasad, “ *Qualitative Analysis of the Bulk Ferromagnetic Hysteresis Model*”, 1998, Proc. 37th IEEE Conf. Dec. Contr., pp 2443-2448, IEEE, New York.

R. Venkataraman and P. S. Krishnaprasad,
“ *A Model for a Thin Magnetostrictive Actuator*”, 1998,
Proc. 32nd Conf. Info. Sci. Syst, pp. 813-818, Princeton University.

E. Justh and P. S. Krishnaprasad, “ *A Lyapunov Functional for the Cubic Nonlinearity Activator-Inhibitor Model Equation,*” 1998,
Proc. 37th IEEE Conf. Dec. Contr., pp 1404-1409, IEEE, New York.

A. J. Newman and P. S. Krishnaprasad,
“ *Computation for Nonlinear Balancing*”, 1998,
Proc. 37th IEEE Conf. Dec. Contr., pp 4103-4104, IEEE, New York.

P. S. Krishnaprasad and V. Manikonda,
“ *Control Problems of Hydrodynamic Type*”, 1998,
invited paper for special session on Control of Underactuated Systems at the
Proc. IFAC Symposium on Nonlinear Control Systems
(NOLCOS'98, Enschede, The Netherlands, July 1-3, 1998), vol 1: 139-144.

V. Manikonda, P. S. Krishnaprasad and J. Hendler, “ *Languages, Behaviors, Hybrid Architectures and Motion Control*”, 1998, invited paper for special volume: Mathematical Control Theory (in honor of the 60th birthday of Roger Brockett), pp 199-226,
(eds. John Baillieul and Jan C. Willems), Springer-Verlag.

G. Kantor and P. S. Krishnaprasad, “ *Efficient Implementation of Controllers for Large Scale Linear Systems via Wavelet Packet Transforms*”, (1998), Proc. of 32nd Conf. Info. Sci. Syst.,
pp. 52-56, Princeton University, Princeton, NJ.

E. Justh and P. S. Krishnaprasad, “ *Analysis of a Complex Activator Inhibitor Equation*”,
Proc. American Control Conference, June 1999, pp 1613-1617.

E. W. Justh, M. A. Vorontsov, G. W. Carhart, L. A. Beresnev and P. S. Krishnaprasad (2001),
“ *Adaptive optics with advanced phase-contrast techniques: part II. High-resolution wavefront control,* ” J. Opt. Soc. Am. A, 18(6):1300-1311.

R. Venkataraman and P. S. Krishnaprasad (2000),
“ *A novel algorithm for the inversion of the Preisach operator,*”
in V.V. Varadan ed. Smart Structures and Materials 2000; Mathematics and

Control in Smart Structures, Proc. SPIE, vol. 3984, pp 404-414

X. Tan, J. S. Baras and P. S. Krishnaprasad (2000), "*Fast evaluation of demagnetizing field in three dimensional micromagnetics using multipole approximation,*" in V.V. Varadan ed. Smart Structures and Materials 2000; Mathematics and Control in Smart Structures, Proc. SPIE, vol. 3984, pp 195-201

X. Tan, J. S. Baras and P. S. Krishnaprasad (2000), "*Computational micromagnetics for magnetostrictive actuators,*" in V.V. Varadan ed. Smart Structures and Materials 2000; Mathematics and Control in Smart Structures, Proc. SPIE, vol. 3984, pp 162-173

G. W. Carhart, M. A. Vorontsov and E. W. Justh (2000), "*Opto-electronic Zernike filter for high-resolution wavefront analysis using a phase-only liquid crystal spatial light modulator,*" in High-Resolution Wavefront Control: Methods, Devices and Applications II, Proc. 45th Annual Meeting of SPIE, 4124: 138-137.

M. A. Vorontsov, E. W. Justh and L. A. Beresnev (2000), "*Advanced phase-contrast techniques for wavefront sensing and adaptive optics,*" in High-Resolution Wavefront Control: Methods, Devices and Applications II, Proc. 45th Annual Meeting of SPIE, 4124: 98-109.

R. Venkataraman and P. S. Krishnaprasad (2000), "*Approximate inversion of hysteresis: Theory and numerical results,*" in Proc. 39th IEEE Conf. Decision and Control, 4448-4454, IEEE, New York.

E. W. Justh, P. S. Krishnaprasad and M. Vorontsov (2000), "*Nonlinear analysis of a high-resolution optical wavefront control system,*" in Proc. 39th IEEE Conf. Decision and Control, 3301-3306, IEEE, New York.

B. Azimi-Sadjadi and P. S. Krishnaprasad (2000), "*Approximate nonlinear filtering and its applications for GPS,*" in Proc. 39th IEEE Conf. Decision and Control, 1579-1584.

P. S. Krishnaprasad (2000), "*Relative equilibria and stability of rings of satellites,*" in Proc. 39th IEEE Conf. Decision and Control, 1285-1288, IEEE, New York.

B. Azimi-Sadjadi and P. S. Krishnaprasad (2001), "*Integer ambiguity resolution in GPS using particle filtering,*" Proc. American Control Conference, 3761-3766, American Automatic Control Council, Phila.

G. Kantor and P. S. Krishnaprasad, "*An application of Lie groups in distributed control networks,*" Systems and Control Letters 43 (2001) 43-52.

X. Tan, R. Venkataraman, and P. S. Krishnaprasad, "*Control of hysteresis: theory and experimental results, Smart Structures and Materials 2001, Modeling, Signal Processing, and Control in Smart Structures,*" Proceedings of SPIE 2001, vol. 4326 101-112.

S. Andersson and P. S. Krishnaprasad "The Berry-Hannay phase of the equal-sided spring-jointed four-bar mechanism," Proc. 40th IEEE Conf. on Decision and Control, 2001, 3406-3407.

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.

F. Zhang, M. Goldgeier and P. S. Krishnaprasad, "Control of Small Formations Using Shape Coordinates", Proceedings of the IEEE Intl. Conference on Robotics and Automation, (May 12-17 Taipei, Taiwan, 2003),

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.

F. 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.

F. 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.

T. Seidman & S. Antman, "Optimal Control of a Nonlinearly Viscoelastic Rod. Control of Nonlinear Distributed Parameter Systems," edited by Chen, G., Lasiecka, I & Zhou, J., Marcel Dekker, 2001, 273--283.

Papers Presented at Meetings, but not Published in Conference Proceedings

E. Justh and P. S. Krishnaprasad, "Pattern Formation for the Control of Large Actuator Arrays", Lecture Notes of the Fourth ARO Workshop on Smart Structures, Penn State University, August 16-18, 1999 (10 pages)

J-Q. Shao and P. S. Krishnaprasad (2000), "Stability analysis of iterative learning controls," in M. Fleiss and A. Eljai eds., Proc. 14th Intl. Symp. Math. Network and Systems (CD), (10 pages).

A. J. Newman and P. S. Krishnaprasad (2000), "Computing balanced realizations for nonlinear systems," in M. Fleiss and A. Eljai eds., Proc. 14th Intl. Symp. Math. Networks and Systems (CD), (10 pages).

Ghalichechian, M. Khbeis, Z. Ma, S. Moghaddam and X. Tan, "A piezoresistive pressure sensor cluster", (poster), MEMS Alliance Special Topics Symposium, The Johns Hopkins University, Applied Physics Laboratory, 2002.

S. Antman, "*The Many Roles of Viscosity in Solid Mechanics.* " Multifield Problems, edited by A.-M. Sandig, W. Schiehlen, and W. L. Wendland, Springer-Verlag, 2000, 1--10.

S. Antman, "*Breathing Oscillations of Rotating Nonlinearly Elastic and Viscoelastic Rings.*" Advances in the Mechanics of Plates and Shells, edited by D. Durban, D. Givoli, and J. G. Simmonds, Kluwer, 2000. pp 1-16.

S. Antman, "*Nonlinear Continuum Physics, Mathematics Unlimited: 2001 and Beyond,*" edited by B. Enquist and W. Schmidt, Springer-Verlag, 2001, pp. 1-21

S. Antman, "*Optimal Control of a Nonlinearly*" Viscoelastic Rod. Control of Nonlinear Distributed Parameter Systems, edited by I. Lasiecka, M. Dekker, 273-283 (with T. I. Seidman)

Manuscripts submitted but not Published

X. Tan, "*Almost symplectic Runge-Kutta schemes for hamiltonian systems*", submitted to BIT, 2002.

X. Tan, J. S. Baras and P. S. Krishnaprasad, "*A dynamic model for magnetostrictive hysteresis*", accepted for Proc. 2003 American Control Conference.

X. Tan and J. S. Baras, "*A robust control framework for smart actuators*", Proc. 2003 American Control Conference.

E. W. Justh and P. S. Krishnaprasad, "*Equilibria and steering laws for planar formations*", Systems and Control Letters, (in press,2003).

S. Antman *Invariant dissipative mechanisms for the spatial motion of rods suggested by artificial viscosity*, Journal of Elasticity, 11 pp.

S. Antman *Regularity properties of planar motions of incompressible rods*, Discrete and Continuous Dynamical Systems B, 16 pp.

T. Seidman and S. Antman, *Optimal control of the spatial motion of a viscoelastic rod*, Dynamics of Continuous, Discrete, and Impulsive Systems, 13 pp., to appear.

E. Justh, P. S Krishnaprasad, and M. Vorontsov, "*Analysis of a high-resolution optical wave-front control system,*" provisionally accepted for publication in Automatica, revised version submitted in September 2003

X. Tan and J. S. Baras, "*Control of hysteresis in smart actuators, part I: Modeling, parameter identification and inverse control and part II: A robust control framework.*" provisionally accepted for publication in Automatica, revised version submitted in August 2003.

Technical Report

X. Tan and J. Baras, "Control of smart actuators: a viscosity solutions approach," Institute for Systems Research Technical Report, TR 2001-39.

E. W. Justh and P. S. Krishnaprasad, "A simple control law for UAV formation flying", Institute for Systems Research Technical Report, TR 2002

Boston University

Peer Review Journal

N. Vandelli, D. Wroblewski, M. Velonis, and T. Bifano, *Development of a MEMS Microvalve Array for Fluid Flow Control*, J. Microelectromechanical Systems, [7], pp. 395-403, 1998.

M. Horenstein, T.G. Bifano, S. Pappas, J. Perreault, and R. Krishnamoorthy-Mali, "Real Time Optical Correction Using Electrostatically Actuated MEMS Devices." Journal of Electrostatics, Vol. 46, pp. 91-101, 1999.

T.G. Bifano, J. Perreault, R.K. Mali, and M.N. Horenstein, "Microelectromechanical Deformable Mirrors," Journal of Selected Topics in Quantum Electronics, [5], pp. 83-90, 1999.

R. Mali, T. Bifano, and D. Koester, "A design-based approach to planarizations in MEMS," Journal of Micromechanics and Microengineering, 1999.

T. Bifano, J. Perreault, R. Mali, and M. Horenstein, "Microelectromechanical Deformable Mirrors," Journal of Selected Topics in Quantum Electronics, [5], February 1999.

M Hornstein, J. Perreault, and T. Bifano, "Capacitive Position Sensor for Double-Cantilevered Micro-machined Actuators," Sensors and Actuators, 1999.

T. Bifano, R. Krishnamoorthy, H. Caggiano, and E. Welch, "Fixed-Load Electrolytic Dressing with Bronze-Bonded Grinding Wheels," ASME J. Manufacturing, [121], pp. 20-27 1999.

M. N. Horenstein, J. Perreault, and T. G. Bifano, "Differential Capacitive Position Sensor for Planar MEMS Structures with Vertical Motion." Sensors and Actuators (80) 2000, pp 53-61

T. Weyrauch, M. Vorontsov, T. Bifano, Hammer JA, Cohen M, Cauwenberghs, "Microscale adaptive optics: wave-front control with a mu-mirror array and a VLSI stochastic gradient descent controller" G APPLIED OPTICS 40 (24): 4243-4253 AUG 20 2001

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

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

Non Peer Reviewed Journal Proceedings and Conference Proceedings

P. Shanbhag, M. Feinberg, T. Bifano, G. Sandri, M. Horenstein, and S. Fawcett, "*Wavelet-based contouring algorithm for sub-millimeter diameter optics*," Proc.12th Annual meeting of the Amer.Soc.

Prec. Eng. , D. Luttrell, Editor, pp.342-345, St. Louis, MO, 1997. Bifano, T., "*Surface micromachined deformable mirrors for adaptive optics*," to be submitted to the SPIE workshop on Adaptive Optics, July 1997.

D. Wroblewski, D. Horenstein, D. Vandelli, M. Velonis, and T. Bifano, "*MEMS Micro-Valve Arrays for Fluidic Control*," Proceedings of 1998 International Mechanical Engineering Congress and Exposition, ASME DSC-Vol. 66, pp 145-152, 1998.

T. Bifano, "*MEMS deformable mirrors for wavefront correction*," High Resolution Wavefront Control Symposium, SPIE vol 3760, July 1999

T. Bifano, "*Control of Smart Structures: Microelectromechanical Systems*," Workshop: Introduction to Smart Materials, Tuesday, December 15, 1998, in conjunction with the 37th IEEE Conference on Decision and Control.

C. Hodge, D. Wroblewski, and T.G. Bifano, "*Evaluation of MEMS Microvalve Arrays as Fluid Controllers*" ASME/JSME Fluids Engineering Division Summer Meeting, Paper Number: FEDSM00-11315, Boston, MA, June 11, 2000.

C. Hodge, D. Wroblewski, and T.G.Bifano, "*MEMS microvalve arrays for fluidic control*," ACTIVE 99, the 1999 International Symposium on Active Control of Sound and Vibration, Fort Lauderdale, Florida, December 02-04, 1999.

S. Cornelissen, T. Bifano, P. Bierden, "*MEMS spatial light modulators with integrated electronics*, Proc. SPIE Vol. 4561, p. 28-34, MOEMS and Miniaturized Systems II, M. Edward Motamedi; Rolf Goering; Eds. 10/2001

T. Bifano, "*Micro-electromechanical spatial light modulators with integrated electronics*, Proceedings of SPIE Vol. 4493, High-Resolution Wavefront Control: Methods, Devices, and Applications III, San Diego, CA, USA, Sponsored by SPIE: Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, USA, August 1-3, 2001.

S-M. Nee, L. DeSandre, T. Bifano, L. Johnson,
Moran, M., *Optical characterization of MEMS deformable mirror array structures*,
“Proc. SPIE Vol. 4447, p. 65-76, Surface Scattering and
Diffraction for Advanced Metrology,” Zu-Han Gu; Alexei A. Maradudin; Eds. 10/2001

T. Weyrauch, M. Vorontsov,
T. Bifano, J. Hammer, M. Cohen, G. Cauwenberghs,
“*Microscale Adaptive Optics: Wave-Front Control with a -Mirror Array and a
VLSI Stochastic Gradient Descent Controller*,” Applied Optics-LP, Vol. 40
Issue 24 Page 4243,

T. Bifano, J. Perreault, P. Bierden, M. Horenstein,
Manufacturing of an optical-quality mirror system for adaptive optics,
Proceedings of SPIE Vol. 4493, High-Resolution Wavefront Control: Methods,
Devices, and Applications III, San Diego, CA, USA, Sponsored by SPIE:
Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, USA,
August 1-3, 2001.

T. Weyrauch, M. Vorontsov, J. Gowens, T. Bifano, *3Fiber coupling with
adaptive optics for free-space optical communication*,² Proceedings of
SPIE Vol. 4489, Free-Space Laser Communication and Laser Imaging, San
Diego, CA, USA, Sponsored by SPIE: Society of Photo-Optical
Instrumentation Engineers, Bellingham, WA, USA, July 30-31, 2001.

J. Baillieul, “*Equilibria and Stability of an n-Pendulum Forced by Rapid
Oscillations*,” 1997 IEEE Conf. on Decision and Control, Dec. 1997, IEEE
Piscataway NH, pp 1147-1152 (with S. Weibel and B. Lehman).

J. Baillieul, “*Oscillatory Control of Bifurcations in Rotating Chains*,”
Proc. of the 1997 American Control Conference, Albuquerque, NM, pp. 2313-1317

J. Baillieul, “*Kinematic Nonholonomic Optimal Control: The Skate Example*,”
1997 IEEE Conference on Decision and Control, 1997, IEEE Piscataway, NJ,
pp. 3054-3060, (with S. Akileswar).

J. Baillieul, “*The Geometry of Controlled Mechanical Systems*,” Mathematical
Control Theory, J. Baillieul and J. Willems, eds., Springer-Verlag, New York, 1998, pp. 322-354.

J. Baillieul, “*Simple Controllable Walking Mechanisms which Exhibit
Bifurcations*,” 1998 IEEE Conf. on Decision and Control, December 1998, Tampa
FL, Published by IEEE, Piscataway, NJ pp. 3027-3032.

J. Baillieul, “*Bifurcations and Stabilization of the Vertically Forced
n-Approaches Infinity*,” 1998 IEEE Conference on Decision and Control, Dec
16-18, Tampa, Published by IEEE, Piscataway, NJ pp. 3587-3592, (with S. Weibel and B. Lehman).

J. Baillieul, “*Averaging and Energy Methods for Robust Open-loop Control
of Mechanical Systems*,” Essays on Mathematical Robotics, J. Baillieul,

S.S. Sastry, and H.J. Sussmann, Eds. IMA Series of Springer-Verlag, 1998, (with S. Weibel and B. Lehman).

J. Baillieul, "*Scale-dependence in oscillatory control of micromechanisms*," to be submitted to the 1998 IEEE Conference on Decision and Control.

J. Baillieul, "*Control Design which respects characteristic length scales in smart systems and smart structures*," 1999. Proc. of SPIE's 6th Annual Int'l Symposium on Smart Structures and Smart Materials, March 1-4, Newport Beach, CA Volume 3667, pp 202-210

J. Baillieul, Preamble to "*An Invariance Principle in the theory of Stability*," in book *Control Theory: Twenty-five Seminal Papers (1931-1981)*, T. Basar, Ed., Wiley/IEEE Press, pp. 309-310, (with Petar Kokotovic).

J. Baillieul, "*Kinematic Asymmetries and the Control of Lagrangian Systems with Oscillatory Inputs*," Proceedings of the IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control, Princeton University, March 16-18, 2000.

M.K. Kanagavel and J. Baillieul, "*The Role of Sensory Feedback and Communication in Organizing the Behavior of Simple Robotic Systems*," Submitted to *Advanced Robotics*, 2000.

A.C. Smith and J. Baillieul, "*Vortex Models for the Control of Flows*," to appear in, The 2000 IEEE Conference on Decision and Control, Sydney, Australia, December 12-15, 2000 (6 pages).

J. Baillieul, "*Matching Conditions and Geometric Invariants for Second-order Control Systems*," Proc. of The 1999 IEEE Conference on Decision and Control, Phoenix, AZ, December, 7-10, pp. 1664-1670.

J. Baillieul, "*Averaging Methods for Force-Controlled and Acceleration-Controlled Lagrangian Systems*," 39-th IEEE Conference on Decision and Control, Sydney Australia, December 12-15, 2000, pp. 1266-72.

A. Smith, and J. Baillieul, "*Vortex Methods For The Control Of Flows*," 39-th IEEE Conference on Decision and Control, Sydney Australia, December 12-15, 2000, pp. 1724-1729. (With A.C. Smith)

J. Baillieul, "*Information and Communication requirements for Intelligent control*," ARO Workshop 2000 on Intelligent Systems, Australian National University, Canberra, Australia December 8-9, 2000.

J. Baillieul, "Open Loop Robust Oscillatory Stabilization of a Two-wire System inside the Snap-through Instability Region," The 2001 IEEE Conference on Decision and Control, Orlando, FL, December, 2001, pp 1334- 1341, (with K.Nonaka).

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 submitted to Journal of Electrostatics (Elsevier).)

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

J. Baillieul, "Feedback Designs in Information-based Control," in 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.

J. Baillieul and A. Suri, "Information Patterns and Hedging Brockett's Theorem in Controlling Vehicle Formations," Proceedings of the 2003 IEEE Conference on Decision and Control, Maui, Hawaii, December 9-12, TuMO2-6, pp.556-563.

A.C. Smith and J. Baillieul, "Vortex Models for the Control of Stall," Proceedings of the 2003 IEEE Conference on Decision and Control, Maui, Hawaii, December 9-12, WeM12-5, pp.407-2412.

K. Li and J. Baillieul, "Robust Quantization for Digital Finite Communication Bandwidth (DFCB) Control," Proceedings of the 2003 IEEE Conference on Decision and Control, Maui, Hawaii, December 9-12, ThAO2-1, pp. 130-3135.

Papers Presented at Meetings but not Published in Conference Proc

T. Bifano, "Surface micromachined MEMS valve arrays," the 1998 *Solid State Sensor and Actuator Workshop*, June 7-11, Hilton Head, SC.

T. Bifano, "MEMS arrays for microfluidics and microoptics" *Control and Dynamical Systems: Invited Lecture Series*, University of Maryland, October 19, 1998.

Personnel

PIs:

Professor Roger Brockett, Harvard University
Professor P.S. Krishnaprasad, University of Maryland
Professor John Baillieul, Boston University
Professor Howard Stone, Harvard University
Professor Stuart Antman, University of Maryland
Professor John Baras, University of Maryland
Professor Tom Bifano, Boston University

Harvard University

Magnus Egerstedt, Postdoctoral Fellow
Richard Day, Postdoctoral Fellow
Dimitrios Hristu, Ph.D. 1999
Kiril Selverov, Ph.D 2001
Jaqueline Ashemore, Ph.D 2002
Alexander Rabiner, MS 2002
Kristi Morgansen, Ph.D. 1999
Navin Khaneja, Ph.D. 2000

other personnel Harvard University:

Sam Pfister
Stan Jurga
Tammy Hepps
Patrick Bose
Pavel Vasilyev
Christopher Juhasz
Javier Sobrado

Boston University

Prashant Shanbhat
Geoffrey Howell, Ph.D. 1999
N. Vandelli, Ph.D. 1999
H. Liu, Ph.D. 1999
P.K. Mali, Ph.D. 1999
M. Feinberg, Ph.D. 1999
Scott Therieault, MSME 2000
John Collier MSME 2000
Greg Riemann
Rober Horacek
D.J Raghunathan, MSME 2002

Keyong Li
Julie Perrault, PhD 2002
Steve Cornelissen, MSME, 2002
Adam Smith
Seung Hoon Lee, Ph.D. 1998
Dhananjay Raghunathan, MSME 2002
Madhan Khanagavel, MSME 2000
Kenichiro Nonaka, Ph.D 2003

Other personnel Boston University

Larry D'Anna
Patrick Sodre
Norman Lo
Yassir Voukhriss
J.-P. Swinski
Andre Botello
Jackie Gallo
Andrea Ruggiero
Matt Chown

University of Maryland

Herbert Struemper Ph D 1997
Vikram Manikonda, Ph. D. 1997
Xiabo Tan, Ph.D. 2002
R. Venkataraman, Ph.D. 1999
George Kantor, Ph.D 1999
Eric Justh, Postdoctoral Fellow
Sean Andersson, Ph.D. 2003
Babak Azimi-Sadjadi, Ph.D 2001
Clifford Knoll
Jin Qiu Shao, Ph.D. 2001
Fumin Zhang,
Amir Handzel, Postdoctoral Fellow

Other personnel University of Maryland

Yassi Boukhriss
Norman Lo
Patrick Sodre
Ryan Braud
Michael Goldgeier
Bharat Madhusudhan

Inventions

Fluidic all Optical Switch, 2002

Wavefront Phase Sensors Based on Optically or Electrically Controlled
Phase Spatial Light Modulators for Wavefront Sensing and Control, 2000