Institute for Systems Research
Graduated NSF Engineering Research Center
Summative Review Site Visit Report
1985-2010

In Memoriam
Susan Frazier
1951–2010

This report is dedicated to the memory of Susan Frazier, one of ISR's original staff members and the author of Section F of the report. Susan was ISR's director of education and human resources. She passed away unexpectedly on October 25, 2010 after routine surgery.

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A. ISR's vision and strategy

ISR's vision. ISR is a permanent, interdisciplinary research unit in the A. James Clark School of Engineering at the University of Maryland. For the past 25 years it has been a home to interdisciplinary research and education activities in the system sciences and systems engineering, with a focus on the communications, control, and computing needed to model and design engineering systems that are highly automated, autonomous and distributed.

We surmise that the next 25 years of research and education will be driven by several new, emerging challenges. Technology today is reaching a capability level that enables us to see, sense and measure with high precision almost any event or quantity of interest. We are rapidly approaching a point where it is possible to connect systems—engineering systems, biological systems, information systems, human and social systems—in ways that were previously impossible. Time-scales for system development will continue to shrink and performance requirements will continue to increase. Not only will future systems need to be rapidly deployed, but their operation will need to be both agile and resilient to uncertainties and rapidly changing environmental conditions.

The design and manufacturing of the needed large-scale (or miniature) systems of the future will require not only expertise in sensing, control and communications, but also in social and human factors. To keep the complexity of design activities in check, future systems engineering methodologies and tools will need to place a priority on the use of formal representations for system architectures, systems behavior, and evaluation procedures. Undergraduate education in critical systems-oriented skills will become mandatory.

ISR's strategy. From an organizational standpoint, ISR is composed of faculty and researchers from 11 departments and four colleges across the university. The underlying motivation for our model is that teams of researchers with diverse backgrounds are needed to address society's most important and challenging problems. We have learned, however, that along with the advantages, there are limitations to exclusive reliance on this approach.

ISR Application Layer
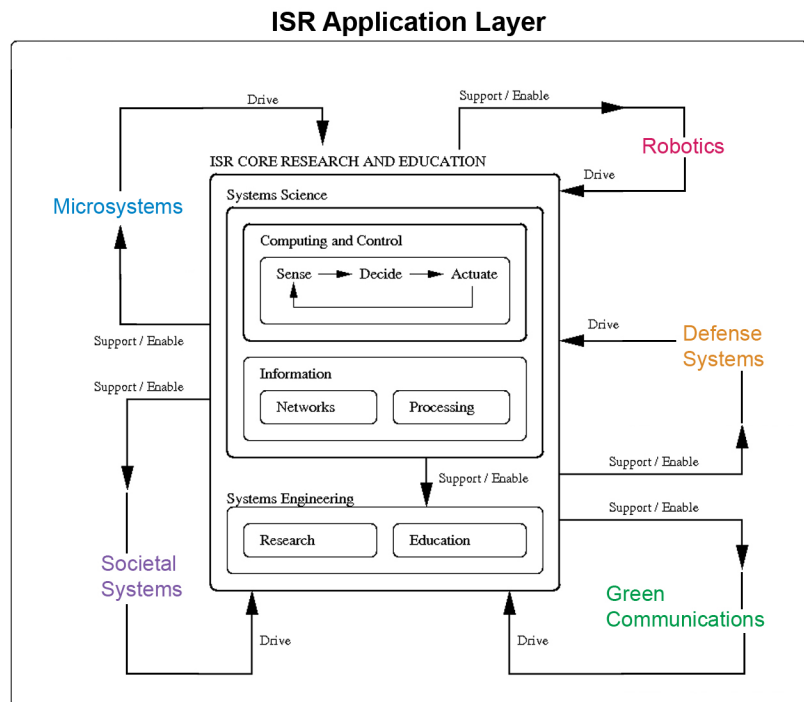
Organization for ISR's core research and education activities, driven by ensembles of applications development.

Without proper management, research projects can deviate from addressing the most critical systems issues associated with ISR's mission. Groups of research projects can become uncoordinated. Opportunities can be lost in highlighting the unique benefits ISR has provided to the larger university community and in describing ISR to a wider audience.

To overcome these limitations and to facilitate ISR's strategic planning, we have modeled ISR with the hierarchical, layered organizational structure shown in the figure above. ISR's long-term mission is defined by the system science and systems engineering activities shown at the center (or core) of the figure. Within the core, advances in systems science support advances in systems engineering research and education. Advances in both the system sciences and systems engineering are driven by a few carefully selected applications (e.g., robotics, microsystems) which, in turn, enable the development of future generations of applications. Each ISR faculty member is expected to contribute to elements of this vision (applications, systems science, systems education).

B. Scientific achievements and impact

1. How has ISR contributed to the evolution of the field of systems science and systems engineering?

ISR's long-standing purpose has been to provide a home to interdisciplinary research and education programs in systems engineering and the system sciences, and to develop basic solution methodologies and tools for systems problems in a variety of application domains. These dual missions are tightly coupled in the sense that large-scale science requires systems engineering and, conversely, systems engineering and implementation of modern real-world systems cannot occur without good systems science.

Broadly speaking, most of ISR's contributions to the system sciences have occurred through a need to model, design, and understand (analyze and simulate) new types of engineering and biological systems that are economically competitive (providing bang for the buck), automated and distributed, readily extensible and adaptable to changing environmental conditions, and resilient to uncertainties.

Today, the frontiers of engineering and biological system development can be pushed because engineers have the tools to support analysis and design. *ISR was at the forefront of creating these tools.* Basic research has resulted in many new algorithms and sophisticated models for decision making and control (sense-decide-actuate lifecycle), communications, and computing needed to support these activities. New approaches to the planning and multi-objective optimization-based design of engineering systems have been developed.

Since ISR faculty are drawn from 11 departments across four colleges, advances in the system sciences have been driven by a wide range of complex applications, which, of course, have changed over time. A few examples include: integrated product and process design for manufacturing applications, helicopter control systems, air traffic control, healthcare systems, mobile ad-hoc communications networks, sensory systems based on the echolocation systems of bats, and fast and small microrobots.

The Systems Research Center that became ISR was created in part to develop formal model-based approaches to systems analysis and systems engineering. Most of ISR's contributions to the first part of this mission have occurred through advances to the systems sciences, with support provided through traditional academic funding mechanisms.

ISR's work and contributions to systems engineering have been far more exploratory. It is important to note that when ISR was created, the systems engineering profession was quite immature—perhaps where control and finite elements were in the mid 1960s. The profession also was stuck in a document-centric mindset. The systems engineering community didn't even have a professional society.

In the early days of ISR, a sizeable disconnect existed between ISR's vision for systems engineering and industry capability. At times, this made the task of forming cooperative working relationships with U.S. industry very difficult. This situation persisted until 1995-2000, when remarkable advances in computing finally created an opportunity for industry to catch up.

During the past decade, there has been an enormous effort within the systems engineering community to develop and implement model-based systems engineering procedures. Visual modeling languages such as UML and SysML are now supported by tools such as MagicDraw and Artisan. The representation and management of very large sets of requirements—millions of requirements—can be handled by tools such as DOORS (Dynamic Object Oriented Requirements System) and IBM Telelogic SLATE. These advances have been facilitated by the International Council of Systems Engineers (INCOSE), which now has a flourishing membership approaching 10,000. For those ISR faculty who have been actively involved in systems engineering research and education, this is nothing less than complete vindication that we were working on the right problems all along.

Today, the discipline of systems engineering can be naturally partitioned into two sub-processes: the systems management process and the technical development process. There are now approximately 20 graduate-level programs in systems engineering offered throughout the U.S. Perhaps for economic reasons, most of these programs emphasize the systems management side of things, where there is considerable overlap with project management.

We, in contrast, have focused on issues associated with the technical development of systems. Therefore, over the years, ISR has contributed substantially to system modeling, system requirements modeling and visualization, integration and optimization of product and process development, and recently, formal approaches to validation and verification through present-day and future approaches to model checking.

It is now abundantly clear that to keep the complexities of future system-level designs in check, increased emphasis on system decomposition, systems abstraction and formal approaches to analysis will be needed. This trend will continue into the near future, where we intend to become internationally recognized for contributions to model-based systems engineering methodologies and tools.

2. To what broad areas of study has ISR contributed significant developments or made unique and special contributions?

Some of ISR's most significant contributions have come in the areas of robust intelligent control, telecommunication wireless and hybrid networks, sensors, optimization, semiconductor manufacturing, signal processing in the auditory cortex, network security, geometric reasoning and planning,

databases, tradeoff analysis, human-computer interaction, artificial intelligence, data mining, neuromorphic engineering, and micro and nano electromechanical systems.

The abstract models are the same, but the applications change from field to field.

3. Did any or all developments or contributions arise from interdisciplinary research?

Yes. Most of our contributions have come from interdisciplinary research.

4. What scientific breakthroughs have emerged from ISR?

Some of ISR's scientific breakthroughs have included cell-based sensors; micro-ball bearing and three-dimensional grayscale microfabrication technologies for micro-engines; multi-criteria, engineered learning systems; integrating product dynamics and process models; actuation and control based on signal processing; multi-part molding for robotics; mobile adhoc networks (MANETs); queuing for mass vaccination clinics; information visualization; real-time process control; speech processing in noisy environments; AI planning; design of hybrid communication networks (satellite/wireless/wireline); design of biologically inspired micro-electronic devices; biological and chemical sensing system design and development for toxin detection; multi-body systems, flocking theory and design; new control approaches for nonlinear systems including stall control of jet engines; and medical applications including control targeting of therapies to tumors.

5. What have been the effects of these breakthroughs on further developments in research?

Mobile adhoc networks (MANETs) were established as a systems research area in the sense that protocols should be investigated jointly—what is now called cross-layer design of wireless networks. In addition, energy efficiency in MANETs was established as an important design consideration.

A model-based systems engineering approach in integrated product process design was established, including object-oriented models of system behavior and structure, and optimization based trade-off analysis. This was motivated by a large project with Westinghouse and Northrop Grumman.

A model-based systems engineering approach to integrated management of hybrid networks was established in joint work with Hughes Network Systems.

ISR research on Hierarchical Task Network (HTN) planning has influenced nearly all subsequent work in this area. The 1994 paper, "A sound and complete procedure for hierarchical task-network planning," by K. Erol, J. Hendler, and D. S. Nau won an ICAPS 2009 Influential Paper Honorable Mention in 2009 because of its long-term impact.

The work led to the development of ISR's SHOP and SHOP2 AI planning programs, which have been downloaded more than 13,000 times and have been used in many hundreds of projects worldwide. The work also has been incorporated into the standard graduate-level textbook on its topic, *Automated Planning: Theory and Practice* by M. Ghallab, D. S. Nau, and P. Traverso.

New modeling, analytic and formal models for cross-layer design of wireless network protocols were developed using a component-based, model-based systems engineering approach. The methodology has already resulted in provably improved protocols.

ISR is a major partner in a new five-year, $5M NSF Cyberphysical grant with Vanderbilt University and the University of Notre Dame, "Systems Engineering of Cyberphysical Systems." General Motors Corporation is a major partner in this effort.

A major effort in wireless network security was established over the last 10 years. This now involves several faculty, with multi-million dollar funding. The effort brought a systems perspective to security of such networks way beyond traditional cryptographic methods. Inspiration from systems control and communications theory and methods were essential. Current work spans integrated security from the physical layer (hardware and signal processing) to protocols, applications and human users.

ISR is a major partner in a new NSF Expeditions in Computing grant developing formal model checking methodology for validation, verification and safety of hybrid systems with several applications including biological and automotive systems.

ISR developed a systematic approach for computer-aided manufacturability analysis of machined parts. This work showed that there might exist a very large (possibly infinite) number of feature-based interpretations for a given part design and brought the problem of existence of alternative interpretations to the attention of the feature recognition community, where additional work is now being done.

An in-mold assembly process has been developed that can be used to create articulated structures without requiring post-molding assembly steps. This process significantly reduces the process cost and enables new design possibilities. It has enabled development of a very light-weight bird-inspired robot. This robot is being used to test new wing designs and understand flapping wing flight.

ISR developed a virtual environment-based virtual assembly system to improve existing training. The system includes a new algorithm that allows it to recognize and classify motions during assembly steps and automatically generate 3D animations and text instructions based on assembly demonstrations in the virtual environment. This capability reduces instruction generation time from several days to few hours. A unique feature of this algorithm is its ability to identify and classify user-defined assembly motion features. The research is being used in a wide variety of applications.

6. How has ISR strengthened interdisciplinary research in its fields of study?

ISR research groups influenced in a substantial manner and established the value of an integrated systems approach in several key technological areas: mobile adhoc wireless networks, network security, supply chain management, semiconductor manufacturing process control, collaborative robotics, collaborative control under communication and other resource constraints, integrated design of Internet over satellite protocols and services, integrated biomorphic systems, neuromorphic engineering specifically in the area of speech, and sound understanding and associated sound-driven systems. Key to this successful influence has been the persistent emphasis of ISR researchers on system models and multi-metric trade-off analysis.

7. Which ISR seminal publications significantly enhanced the knowledge base or changed the way we think?

Krishnaprasad, P. S. and J.E. Marsden, "Hamiltonian Structures and Stability for Rigid Bodies with Flexible Attachments," *Archive for Rational Mechanics and Analysis,* vol. 98, no. 1, pp. 71–93, 1987. (also Report of the Center for Pure and Applied Mathematics, University of California, Berkeley, PAM–276, 38 pages, 1985).

Krishnaprasad, P. S., J. C. Simo, and J. E. Marsden, "The Hamiltonian Structure of Nonlinear Elasticity: The Convective Representation of Solids, Rods, and Plates," *Archive for Rational Mechanics and Analysis,* vol. 104, no. 2, pp. 125–183, 1988.

Baras J. S., R. Elliott and M. Kohlmann, "The Partially Observed Stochastic Minimum Principle," *SIAM Journal on Control and Optimization,* Vol. 27, No. 6, pp. 1279–1292, November 1989.

Tassiulas L. and A. Ephremides, "Jointly optimal routing and scheduling in packet radio networks," *IEEE Transactions on Information Theory,* Vol. 38, No. 1, pp. 165–168, January 1992.

Tassiulas L. and A. Ephremides, "Stability properties of constrained queueing systems and scheduling for maximum throughput in multihop radio networks," *IEEE Transactions on Automatic Control,* Vol. 37, No. 12, pp. 1936–1949, December 1992.

Krishnaprasad, P. S., "Dissipation Induced Instabilities," *Annales de L'Institut Henri Poincaré: Analyse Non Lineare,* vol. 11, no. 1, pp. 37–90, (with A.M. Bloch, J.E. Marsden, T.S. Ratiu), 1994.

Wang K. and Shamma S., "Wavelet Representations of Sound in the Primary Auditory Cortex," *J. Optical Engineering,* 33(7), 2143–2148, 1994.

Lin J., Edwards T., and Shamma S., "Analog VLSI Implementations of Auditory Wavelet Transforms," *IEEE Trans Cir. Sys.* 41(8), 572–583 1994.

Erol, K., D. Nau and J. Hendler, "A sound and complete procedure for hierarchical task–network planning," *Proc. International Conf. on AI Planning Systems* (AIPS), pp. 249-254, June 1994. (Honorable mention for International Conference on Automated Planning's Influential Paper Award, 2009)

James M. R. and J.S. Baras, "Robust H∞ Output Feedback Control for Nonlinear Systems," *IEEE Transactions on Automatic Control,* Vol. 40, No. 6, pp. 1007–1017, June 1995.

Wang K. and Shamma S., "Time-Frequency Representations in the Auditory System," *J. Eng. Med. Biol.,* 14(2), 186–194, 1995.

Wang K. and Shamma S., "Representation of Acoustic Signals in The Primary Auditory Cortex," *IEEE Trans. Audio and Speech Processing,* 3(5), 382–395, 1995.

Shamma S., Versnel H., and Kowalski N., "Ripple Analysis in the Ferret Primary Auditory Cortex. I. Response Characteristics of Single Units to Sinusoidally Rippled Spectra," *J. Auditory Neuroscience,* 233–254, 1995.

Shamma S., Versnel H., "Ripple Analysis in the Ferret Primary Auditory Cortex. II. Prediction of Unit Responses to Arbitrary Spectral Profiles," *J. Auditory Neuroscience,* 255–270, 1995.

Versnel H., Shamma S., and Kowalski N., "Ripple Analysis in the Ferret Primary Auditory Cortex. III. Topographic and Columnar Distribution of Ripple Response Parameters," *J. Auditory Neuroscience,* 271–285, 1995.

James M. R. and J.S. Baras, "Partially Observed Differential Games, Infinite Dimensional HJI Equations, and Nonlinear H∞ Control," *SIAM Journal on Control and Optimization,* Vol. 34, No. 4, pp. 1342–1364, July 1996.

Brockett R. W. and W.S. Wong, "Systems with Finite Bandwidth Constraints I: State Estimation Problems," *IEEE Trans. Automatic Control,* vol 42, pp. 1294–1298, 1997.

Brockett R. W., "A Rational Flow for the Toda Lattice Equations," in *Operators, Systems, and Linear Algebra* (U. Helmke et al. eds.), B.G. Teubner, Stuggart, 1997.

Krishnaprasad, P. S., A.M. Bloch, J.E. Marsden, and R.M. Murray, "Nonholonomic Mechanics and Symmetry," *Archive for Rational Mechanics and Analysis,* vol. 136, pp. 21–99, 1997.

Baras J. S. and N.S. Patel, "Robust Control of Set-Valued Discrete Time Dynamical Systems," *IEEE Transactions on Automatic Control,* Vol. 43, No. 1, pp. 61–75, January 1998.

Nau D., M. Ball, J. Baras, A. Chowdhury, E. Lin, J. Meyer, R. Rajamani, J. Splain and V. Trichur, "Generating and Evaluating Designs and Plans for Microwave Modules," *AI for Engineering Design, Analysis and Manufacturing* (AI–EDAM), Vol. 14, No. 4, pp. 289–304, September 2000.

Brockett R.W., N. Ferrier and D. Hristou, "The Performance of a Deformable-Membrane Tactile Sensor: Basic Results on Geometrically-Defined Tasks," *IEEE Int'l Conf. on Robotics and Automation*, 2000.

Krishnaprasad, P. S. and D. Tsakiris, "Oscillations, SE(2) Snakes and Motion Control: A Study of the Roller Racer," *Dynamical Systems,* vol. 16, no. 4, pp. 347–397, 2001.

Bharadwaj V. G., J.S. Baras and N.P. Butts, "An Architecture for Internet Service via Broadband Satellite Networks," *International Journal of Satellite Communications,* Vol. 19, Issue 1, pp. 29–50, January 2001.

Poovendran R. and J.S. Baras, "An Information Theoretic Approach for Design and Analysis of Rooted-Tree Based Multicast Key Management Schemes," *IEEE Transactions on Information Theory,* Vol. 47, No. 7, pp. 2824–2834, November 2001.

Zhao, Z., M. Ball and C.-Y. Chen, "A Scalable Supply Chain Infrastructures Research Test-Bed," in *Scalable Enterprise Systems: An Introduction to Recent Advances,* Prabhu, V., S. Kumara, M. Kamath, eds., Kluwer Academic Publishers, Boston, pp 217–248, 2003.

Vossen, T., Ball, M.O., Hoffman, R. and Wambsganss, M., "A General Approach to Equity in Traffic Flow Management and its Application to Mitigating Exemption Bias in Ground Delay Programs," *Air Traffic Control Quarterly,* 11, 277–292. (a preprint was published in Proceedings of 5th USA/Europe Air Traffic Management R&D Seminar, 2003), 2003.

Ball, M.O., Hoffman, R., Odoni, A. and Rifkin, R., "A Stochastic Integer Program with Dual Network Structure and its Application to the Ground-Holding Problem," *Operations Research.* 51, 167–171, 2003.

Ball, M.O., G. Donohue and K. Hoffman, "Auctions for the Safe, Efficient and Equitable Allocation of Airspace System Resources," in Cramton, P., Y. Shoham and R. Steinberg, eds. *Combinatorial Auctions,* MIT Press, Cambridge, pp 507–538, 2005.

Krishnaprasad P. S., X. Tan and J. S. Baras, "Control of Hysteresis in Smart Actuators with Application to Micro-Positioning." *Systems and Control Letters,* vol. 54, no. 5, pp. 483–492, 2005.

Zhao, Z., M. Ball and M. Kotake, "Optimization-Based Available-to-Promise and Multi-Stage Resource Availability," *Annals of Operations Research,* 135, 65–85, 2005.

Ghose K., T. K. Horiuchi, P. S. Krishnaprasad, and C. F. Moss (2006) Echolocating Bats Use a Nearly Time-Optimal Strategy to Intercept Prey. *PLoS Biology* 4(5): e108. doi:10.1371/journal.pbio.0040108, 2006.

Pruessner M. W., N. Siwak, K. Amarnath, S. Kanakaraju, W-H Chuang, and R. Ghodssi, "End-coupled optical waveguide MEMS devices in the indium phosphide material system," J. Micromech. Microeng. 16 832, doi: 10.1088/0960-1317/16/4/021, 2006.

Georgiadis L., M. Neely, and L. Tassiulas, "Resource allocation and cross-layer control in wireless networks," *Lecture Notes, Foundations and Trends in Networking,* Vol. 1, No. 1, NOW Publishers, Inc. 2006.

Theodorakopoulos G. and J. S. Baras, "On Trust Models and Trust Evaluation Metrics for Ad-Hoc Networks," *Journal of Selected Areas in Communications, Security in Wireless Ad-Hoc Networks,* Vol. 24, Number 2, pp. 318–328, February 2006. [2007, IEEE Communications Society Leonard G. Abraham Prize].

Xi W., X. Tan and J.S. Baras, "Gibbs Sampler-based Self-organization of Autonomous Swarms," *Automatica*, pp. 1107–1119, July 2006.

Elhilali, M, J Fritz, Tai-Shih Chi, S. Shamma "Auditory Cortical Receptive Fields: Stable Entities with Plastic Abilities," *J. Neuroscience* 27(39):10372–10382, 2007.

Fritz J, M. Elhilali, and S. Shamma "Adaptive changes in cortical receptive fields induced by attention to complex sounds," *J. Neurophysiology* 98: 2337–2346, 2007.

Subrahmanian, V. S., "Cultural Modeling in Real Time," *Science*, 317 5844, 1509–1510, DOI: 10.1126/science.1148306, 2007.

Baras J. S., "Security and Trust for Wireless Autonomic Networks: System and Control Methods," *European Journal of Control: Special Issue,* Volume 13, Number 2–3, pp. 105–133, March-June 2007.

Gerasopoulos K., M. McCarthy, E. Royston, J. N. Culver, and R, Ghodssi, "Nanostructured nickel electrodes using the Tobacco mosaic virus for microbattery applications," *Journal of Micromechanics and Microengineering,* 18 104003, doi: 10.1088/0960-1317/18/10/104003, 2008. (Selected for Highlights of 2008 by the *Journal of Micromechanics and Microengineering*)

Aytekin M., C. F. Moss, and J. Z. Simon, "A Sensorimotor Approach to Sound Localization," *Neural Computation* 20:3, 603-635, 2008.

Yu P., J.S. Baras, and B. M. Sadler, "Physical Layer Authentication," *IEEE Transactions on Information Forensics and Security,* Vol. 3, No. 1, pp. 38–51, March 2008.

Elhilali M., J. Xiang, S. Shamma, J. Z. Simon, "Interaction between Attention and Bottom-Up Saliency Mediates the Representation of Foreground and Background in an Auditory Scene," *PLoS Biology,* 7(6): e1000129. doi:10.1371/journal.pbio.1000129, 2009.

Hopkins J. K., B. W. Spranklin and S. K. Gupta, "A survey of snake-inspired robot designs," *Bioinspiration & Biomimetics,* 4 021001, doi: 10.1088/1748-3182/4/2/021001, 2009. (Chosen for the journal's "Highlights of 2009" collection)

Cardenas A., S. Radosavac, and J. S. Baras, "Evaluation of Detection Algorithms for MAC Layer Misbehavior: Theory and Experiments," *IEEE/ACM Transactions on Networking (TON)*, Vol. 17, No 2, pp. 605–617, April, 2009.

Krishnaprasad, P. S., E. Wei and E. W. Justh, "Pursuit and an Evolutionary Game," *Proceedings of the Royal Society of London A,* 465, 1539–1559, 2009.

Luo X., D. L. Berlin, J. Betz, G. F. Payne, W. E. Bentley and G. W. Rubloff, "In situ generation of pH gradients in microfluidic devices for biofabrication of freestanding, semi-permeable chitosan membranes," *Lab on a Chip,* 2010, 10, 59-65, DOI: 10.1039/B916548G, 2009. (Selected for *Highlights in Chemical Technology* 2009, Royal Society of Chemistry.)

Baras J.S. and G. Theodorakopoulos, "Path Problems in Networks," *Lecture Notes, Synthesis Lectures series,* Morgan & Claypool Publishers, January 2010.

Yovel Y., B. Falk, C. F. Moss and N. Ulanovsky, "Optimal Localization by Pointing Off Axis," *Science* 5 February 2010 327: 701-704, DOI: 10.1126/science.1183310, 2010.

Bandyopadhyay S., S. Shamma and P. Kanold, "Dichotomy of functional organization in the mouse auditory cortex," *Nature Neuroscience,* 13, 361–368, doi:10.1038/nn.2490, 2010.

Fritz J., S.V. David, S. Radtke-Schuller, P.Yin, and S.A. Shamma, "Adaptive, behaviorally gated, persistent encoding of task-relevant auditory information in ferret frontal cortex," *Nature Neuroscience,* 13, 1011–1019, doi:10.1038/nn.2598, 2010.

Chiu, C., P.V. Reddy, W. Xian, P. S. Krishnaprasad, and C. F. Moss, "Effects of competitive prey capture on flight behavior and sonar beam pattern in paired big brown bats, Eptesicus fuscus." *J. Exp. Biol.* 213, 3348-3356. 2010.

Tytell, E. D., C-Y Hsu, T. L. Williams, A. Cohen and L. J. Fauci, "Interactions Between Internal Forces, Body Stiffness, and Fluid Environment in a Neuromechanical Model of Lamprey Swimming," *Proceedings of the National Academy of Sciences of the United States of America,* 10.1073/pnas.1011564107, 2010.

C.   Influence as a model for academic research

1. How has ISR served as a model for other research institutes in interdisciplinary research?

The ISR model has been emulated around the world:

• The ACCESS Center in the Royal Institute of Technology (KTH), Sweden

• ELLIT-Excellence Center at Linköping-Lund in Information Technology, Sweden

• Linköping University—Control, Autonomy, and Decision-making in Complex Systems, CADICS—Linnaeus Center, Sweden

• Lund University—LCCC—Lund Center for Control of Complex Engineering Systems – Linnaeus Center, Sweden

• Computer and Automation Research Institute (CARI), Hungarian Academy of Sciences, Hungary

• Research School of Information Sciences and Engineering, Australian National University, Australia

• And even in the creation of the Division of Systems Engineering (across departments at the Massachusetts Institute of Technology, with joint appointments for the first time in the history of MIT) in 1999.

Within the University of Maryland, the ISR model is always used as The Model for institutes on campus. The latest example is the new Institute for Bioscience and Biotechnology (IBB). When the University of Maryland Biotechnology Institute in Baltimore was dissolved and the researchers came to the University of Maryland College Park campus, Provost Nariman Farvardin recommended they form an institute like ISR, which led to talks with us and the IBB being organized along the lines of ISR.

ISR's rigorous systems research focus and emphasis on methodologies also has been influential. Before the ERC program brought ISR to Maryland, systems thinking was not the norm. As was true in much of academia, engineering research was "done in silos" with little cross-communication. ISR opened up opportunities for people to collaborate across departments, which led to a new emphasis on interdisciplinary research.

2. What have been ISR's national and international impacts on the research community in influencing directions and agendas?

The broadest impact of ISR has been the clear recognition and promotion of the idea that a proper integration of core systems principles and disciplinary specialties of engineering and applied science (electronics, mechanical and aerospace sciences, materials science, harmonic analysis, parallel computation, etc.) is key to achieving major advances in emerging technological domains.

This has meant a convergence of control, communication and computing with the disciplinary specialties. This process, begun under the NSF Engineering Research Centers Program in ISR, is now a widely acknowledged means to unlocking the potential of basic research to contribute to the economic and social betterment of humanity. The extraordinary influence and ubiquity of mobile information technologies and their integration in everyday life is just one indication of the impact of this convergence. Other emerging directions such as personal and networked robotics are also benefiting from this process.

Internationally, at the level of foundational research, ISR has deeply influenced research directions and agendas in

the following areas: communication and signal processing algorithms that are efficient in meeting resource constraints and requirements of error-tolerance; architectures for communication networks that enhance mobility and adaptability; analysis and design of algorithms for control of data networks and distributed systems with real-time constraints; control in the presence of uncertainty, complex hybrid dynamics, and limited information; nonlinear science of interacting systems arising in robotics in terrestrial, aerospace, and underwater settings; manufacturing processes for electronic materials that exploit real-time sensing and feedback control; fundamental understanding of the performance and biological basis of signal processing in the mammalian brain; optimization principles and algorithms for large-scale distributed systems.

ISR's foundational research accomplishments benefited from a balanced program of theoretical and experimental investigation. The experimental investigations have led to stronger coupling of these advances to a variety of high visibility, multi-year projects. This has greatly extended the reach and influence of ISR research into the international research community.

Some of these projects generated intellectual property and collaborative developments with industry that also yielded significant commercial benefits. In particular we note projects that were and/or are centered on problems of network security; mobile and sensor networks; hybrid satellite and terrestrial communication networks; manufacturing and product realization systems; MEMS sensor and actuator design and fabrication; nanotechnology with an emphasis on the biomolecular realm; analog VLSI approach to neuromorphic engineering of sensory/signal processing architectures; multimedia technologies emphasizing information integrity; software tools for representation of systems engineering methodologies; languages for motion control and distributed control; algorithms and software for supply chain management; tools for management of transportation systems such as air traffic scheduling; and energy-efficient technologies.

The work of ISR has had a strong basis in quantitative modeling that can be subject to automated verification and validation processes. From the early days, this has meant that (domain-dependent) mixed symbolic-numeric representations of system behavior played an important role in ISR work. Graphical modeling languages also have played an important role, for instance SIMULINK for control systems. Progress in this direction now makes available universal tools such as SysML which is a centerpiece of ISR efforts to propagate systems engineering methodology to a very broad array of problem domains. ISR has been "ahead of its time" in pushing system models, and is poised to have a huge impact in model-based systems engineering research and education.

The power of systems thinking in the cyber-physical era cannot be overstated.

3. What are successful examples of partnerships between ISR and other research institutes, and with what effects?

Research boundaries at the University of Maryland are fluid, and ISR often works with other research institutes on campus. There is a lot of overlap between campus entities because relationships are so facile.

ISR has pursued many Multidisciplinary University Research Initiatives (MURIs) in partnership with the university's other research institutes.

For example, ISR's P. S. Krishnaprasad participated in the Maryland portion of the 2007 MURI, "Exploiting Nonlinear Dynamics for Novel Sensor Networks." He worked with colleagues from the university's Institute for Physical Science and Technology and Institute for Research in Electronics and Applied Physics. The research developed novel nonlinear dynamics-based concepts, devices and networks, yielding a new class of cost-effective, rugged, low-power, resistant to jamming, compact, stealthy military sensors and sensor systems.

Another example is the 2006 MURI, "Cognitive Architecture for Reasoning about Adversaries." The Maryland portion of this award featured ISR's Dana Nau (joint appointment with Computer Science), ISR-affiliated faculty member V. S. Subrahmanian (University of Maryland Institute for Advanced Computer Studies and Computer Science) and ISR's Michael Fu (joint appointment with the Robert H. Smith School of Business). Other participants included Philip Resnik (Linguistics); Jonathan Wilkenfeld (Government and Politics); Lise Getoor (Computer Science and University of Maryland Institute for Advanced Computer Studies); Barry Silverman (University of Pennsylvania); and Marvin Weinbaum, a cultural expert on Afghanistan and Pakistan. The project developed theory and algorithms for a cognitive architecture for reasoning about adversaries.

ISR also has a history of working with research institutes at educational institutions beyond the University of Maryland. MURIs are the obvious example here, and there have been many of them over the years.

For example, in 2005, Anthony Ephremides, Sennur Ulukus (ISR joint appointment with Electrical and Computer Engineering), and Leandros Tassiulas (1992 electrical engineering Ph.D., advised by Ephremides, now a professor at the University of Thessaly, Greece) were part of a MURI for "DAWN: Dynamic Ad-Hoc Wireless Networking." The award addressed energy efficiency, cross-layer optimization, interaction between physical layer, MAC, routing, compression, and scalability of protocols. Other participating institutions were the University of California, Santa Cruz; Massachusetts Institute of Technology; Stanford University; the University of Illinois Urbana-Champaign; the University of California, Berkeley; and the University of California, Los Angeles.

In addition to MURIs, ISR has shared large grants with researchers in other educational institutions throughout its history.

For example, Carol Espy-Wilson (ISR joint appointment with Electrical and Computer Engineering) is part of a 2009 $2.7 million grant from the National Cancer Institute's Division of Cancer Control and Population Sciences (DCCPS), part of the U.S. National Institutes of Heath (NIH). "Predictors of Speech Quality after Tongue Cancer Surgery" partners Espy-Wilson with Maureen Stone of the University of Maryland Dental School, and Jerry Prince of Johns Hopkins University's Whiting School of Engineering.

Another example is Rajeev Barua (ISR joint appointment with Electrical and Computer Engineering) and Rance Cleaveland's (ISR joint appointment with Computer Science) 2009 DARPA research grant, "Adaptive Environment for Supercompiling with Optimized Parallelism (AESOP)." Reflecting the belief that serial computer programs will continue to represent the vast majority of programs in the world, AESOP will develop a state-of-the-art compiler that can automatically compile serial programs into parallel programs to a wide variety of platforms. The ISR researchers are collaborating with BAE Systems Inc. and Princeton University on a $11.5 million program.

Internationally, ISR has partnered with researchers in Swedish and Russian institutes, the SAS Institute and others, and in 2011 will be exploring partnerships with researchers in the Autonomous Province of Trento, Italy.

ISR's collaborations have resulted in new areas of research, cross fertilization, and long exchange visits for faculty and students in ISR, as well as better career opportunities for ISR graduates and improved collaboration with industry and transfer of technology.

You can view a list of major research awards to ISR from the past decade online at *www.isr.umd.edu/research/major_awards.htm*.

4. How successful have ISR faculty and alumni (graduates, postdoctoral researchers, etc.) been in serving as ambassadors and influential proponents of ISR's core missions in academe?

Faculty. Within the university, ISR, its systems thinking and methodologies have been welcomed in the nanoscience and biology programs in which our faculty participate. In addition, both former Director Gary Rubloff and current Director Reza Ghodssi are very involved in Bioengineering through their association with Department Chair William Bentley.

The Department of Energy's new Energy Frontier Research Center (EFRC) at the University of Maryland, begun in 2009, is another example. Led by Gary Rubloff as director, the team includes faculty groups from the Clark School and the College of Computer, Math and Natural

Sciences who are part of the University of Maryland Energy Research Center (UMERC) and the Maryland Nano-Center, which Rubloff also directs. The EFRC will address how nanostructures formed from multiple materials behave and assess their potential for a new generation of electrical energy storage technology.

In many of these new research areas it is currently too early to take full advantage of systems thinking and methodologies. However, the presence and influence of ISR faculty will help the areas rapidly move forward within the university to the benefit of each line of research.

ISR faculty often have the opportunity to be proponents of our core missions beyond the University of Maryland. Sometimes this happens when faculty headline workshops, as will be the case for John Baras at an upcoming workshop with the U.S. Centers for Disease Control. Other times the events are sponsored by ISR itself, as with the Green Communications Workshop chaired by Tony Ephremides (ISR joint appointment with Electrical and Computer Engineering), held this Oct. 14–15 at the university.

Alumni. In preparing this report, we surveyed several dozen of our alumni, asking about the influence ISR has had on their careers, and in the academic, industrial and government settings in which they lead.

Several alumni in academe cited the ability to teach non-classic courses in their fields as a direct result of their interdisciplinary experience at ISR. Some wrote about how systems thinking is advantageous in their work and how training others to think that way is a priority. Others mentioned how the real-world applications of ISR are helping them to improve things today in their settings.

Following is a sampling of typical comments. A select list of ISR alumni by research area and their current places of employment is included in the report appendix.

Ingar Grev is director of program operations at Raytheon Photon Research Associates, Inc. He earned ISR's MSSE degree in 1998 and an MBA from Maryland in 2005, advised by Michael Ball (ISR joint appointment with the Robert H. Smith School of Business). Grev says, "My time with ISR helped me to become a strategic thinker. I always have my eye on the big picture of how everything interfaces—machines, people, organizations, the environment, etc. In my business, systems thinking is a huge advantage because it allows me to push my clients to think outside of their boxes. Business owners get myopic, and the whole reason coaching is valuable to them—especially what we do—is that we force them to break their paradigm."

Eric W. Justh is an electronics engineer specializing in tactical electronic warfare at the Naval Research Laboratory. He earned a Ph.D. in electrical engineering in 1998, advised by P. S. Krishnaprasad (ISR joint appointment in Electrical and Computer Engineering), and still works with Krishnaprasad on research projects of mutual interest. "I was hired due to specific electronics experience that I had," Justh says. "But now, just a few years later, I am predomi-

nantly involved in systems projects. It is very difficult to succeed—or even get hired—here without a strong background in electronics or physics. But add to that a systems and control background, and the possibilities are wide open for making very significant contributions to the organization. I can't imagine what my career would be like now without ISR influence, which is still ongoing through my collaborations with Krishna. The greatest value of my ISR training may well turn out to be in enabling my coworkers to stay focused on the parts of projects that best match their interests and capabilities, while still ensuring that at the end of the project, the various pieces tie together properly to create a working system. In other words, systems expertise can be a magnifier for the conventional expertise present in our organization."

Stephan Koev is a postdoctoral researcher in the Nanoscience and Technology Cooperative Research Program at the National Institute of Standards and Technology. He earned his electrical engineering Ph.D. in 2009, advised by Reza Ghodssi. Koev writes, "My association with ISR as a student helped me by promoting interactions with researchers from other fields. This broadened my skill set and, more importantly, gave me confidence that I can solve problems beyond my immediate area of concentration. I believe that this will help me make better informed decisions throughout my career. In my present position as a postdoctoral research associate, I am heavily using my interdisciplinary background. I use my skills in areas such as microfabrication, metrology, optics, and even software to solve challenging research problems in the field of nanoscale optics. This kind of work cannot be done by a narrowly trained individual."

Fumin Zhang is an assistant professor of Electrical and Computer Engineering at the Georgia Institute of Technology. He earned his Ph.D. in electrical engineering in 2004, advised by P. S. Krishnaprasad. Zhang won an NSF CAREER Award for "Feasibility of Control Tasks—Towards Control-Computing-Power Co-Design" in 2009 and an Office of Naval Research Young Investigators Award for "Generic Environment Models (GEMs) for Agile Marine Autonomy," in 2010. Zhang writes, "ISR provided a unique environment where the leading experts in systems theory from different disciplines gathered. This allowed me to develop a systems view of various fields of applications. It has proven to be an invaluable experience. I have developed a well-funded research and teaching program in Georgia Tech around two themes: marine autonomy and cyber-physical systems theory. A systems-focused training has helped me to unite these fields together under the same framework. Based on the systems models, we are able to develop transformative solutions for real world problems. We have seen significant improvements over existing methods in a number of cases. We are now supported by NSF to bring marine robots developed by students to the Louisiana coast and use systems theory to help survey the estuarine environment polluted by oil spills."

Kaushik Ghose is a research associate in neurobiology at Harvard University. He earned his Ph.D. in electri-

cal engineering advised by Timothy Horiuchi (ISR joint appointment with Electrical and Computer Engineering). Afterwards, he was a postdoctoral researcher with Horiuchi, P. S. Krishnaprasad and Cynthia Moss (ISR joint appointment with Psychology). Ghose says, "The interdisciplinary aspect—being able to collaborate with several professors with different backgrounds—was immensely important. It allowed me to fuse ideas from biology and engineering under great guidance. I'm currently working in a lab that does research in behaving non-human primates. My joint background in neuroscience and engineering nurtured at ISR helps me to approach experiment design, equipment design and data analysis in a more rounded way that I would have been able to otherwise. I am currently investigating how signals from different parts of the cortex are integrated together to guide behavior. My collaboration with Cynthia Moss prepared me for designing the delicate psychophysical task required in the experiment. The experiment requires the measurement of delicate differences in behavior based on a neurophysiological manipulation for which experience in psychophysics is very important. My collaboration with Timothy Horiuchi in circuit design and electronics prepared me for elements of equipment design related to a neurophysiological manipulation (electrical microstimulation) that I am doing in the experiment. My collaboration with P. S. Krishnaprasad in mathematical analysis of the data I collected during my doctoral work prepared me to approach my data analysis using different mathematical techniques that allowed me new insight into my current scientific experiment."

Robert Hoffman is a manager at Metron Aviation, a company that is part of the NEXTOR consortium. He earned a Ph.D. in applied mathematics in 1997, advised by Michael Ball, and also did postdoctoral work at ISR. Hoffman notes, "My graduate and postdoctoral work led directly to my job of the last 11 years. My experiences at ISR gave me contacts and viewpoints I never would have received in the math department. I was able to tap into a diverse set of professors and students, coming from backgrounds such as civil engineering, math, road transportation, and the business school. Those working relations continue to this day. In addition, maintaining my university relationships has kept a pipeline of research ideas and dollars open to my company. More importantly, my work has been able to maintain a fine balance between academic acceptance and applicability. Much of my work has led to immediate improvements in the national air transportation system, via the FAA."

5. What is the international stature of ISR's faculty and programs?

Using any measurement, ISR is at least very competitive in the fields of research we have entered. In certain areas we are among the leaders: communication, control, neuroscience, MEMS, operations research, and manufacturing.

ISR faculty have given more than 20 plenary addresses at international conferences in the past four years. ISR faculty include 44 Fellows of academic societies and 42 NSF CAREER and other Young Investigator awards.

In the past six years, ISR faculty have published in the *Journal of Experimental Biology, Nature Neuroscience, Nature, MRS Bulletin, Proceedings of the National Academy of Sciences, Bioinspiration and Biomimetics, Science, Lab on a Chip, Journal of Microelectromechanical Systems, Langmuir, Advanced Functional Materials, Highlights in Chemical Technology, PLoS Biology, Journal of Neuroscience, Journal of Micromechanics and Microengineering, Proceedings of the Royal Society A, Management Science, Neural Computation, International Journal of Human-Computer Interaction* (a special issue honoring ISR's Ben Shneiderman)*, European Journal of Control, DISCOVER Magazine, IEEE Journal on Selected Areas in Communications, Cerebral Cortex, Operations Research, Management Science, INFORMS Journal on Computing,* and *Computers and Operations Research, Journal on Applied Signal Processing, IEEE Transactions on Signal Processing, IEEE Transactions on Information Forensics and Security,* and *Physical Review Letters*, among other journals.

ISR faculty also have won prestigious national and international awards in their fields. For example, P. S. Krishnaprasad won the IEEE Bode Prize in 2007 *"for fundamental contributions to the theory of control of natural and synthetic physical systems."* The prize, given by the IEEE Control Systems Society, recognizes distinguished contributions to control systems science or engineering.

ISR affiliated faculty member Ben Shneiderman (Computer Science) was inducted into the National Academy of Sciences in 2010.

S.K. Gupta (joint appointment with Mechanical Engineering) won a Presidential Early Career Award for Scientists and Engineers (PECASE) Award in 2001 for his work on developing a new molding process and decision support tool that makes it possible to cost-effectively manufacture multi-material parts. The PECASE is the highest honor bestowed by the U.S. government on outstanding scientists and engineers beginning their independent careers and the awards are conferred annually at the White House.

Over the years, several ISR faculty have won the American Automatic Control Council's O. Hugo Schuck Best Paper Award for Theory: former Director Eyad Abed (ISR joint appointment with Electrical and Computer Engineering) in 1993, Miroslav Kristic (University of California, San Diego) during his tenure at Maryland in 1995, and most recently in 2006, Nuno Martins (ISR joint appointment with Electrical and Computer Engineering).

A select list of awards won by ISR faculty can be found on ISR's web site at *www.isr.umd.edu/faculty/honors_awards.htm*. A list of ISR patents is available at *www.isr.umd.edu/research/patents.htm*.

D. Research Strategic Plan— Past and Future

1. Did engineered systems technology issues drive the research strategy under NSF funding and beyond or was it focused on systems as a field of engineering science, as an enabling suite of methods? Are the future directions proposed motivated by engineered systems or field goals?

ISR has been committed to a balanced program of research and education in the methodologies of system science and engineering, as well as in solving problems that are at root technological, addressing the needs of engineered systems. Thus at ISR the answer is "both." ISR methodological research accounts for about two-thirds of what the institute does, while about one-third of ISR research is in the invention and realization of new technologies that exploit this research.

In the beginnings of ISR as an engineering research center, the methodologies of interest were founded and organized within the core systems principles domains of control theory, communication theory, optimization theory and computation, as being vital to the solution of a broad range of problems in engineered systems. While the vitality of these core disciplines continues unabated and remains very relevant to the ISR mission, other scientific domains have proved to be critical as well.

For instance, a focus in neuroscience has proved influential in the advancement of signal processing principles and solutions, and in the creation of novel neuromorphic architectures for intelligent systems. A focus on materials science and its interface with biomolecular complexity is driving the creation of nanoscale technologies for sensing and manipulation, and the energizing of these technologies. A focus on new methods of encryption, distributed algorithms and related mathematics is proving essential to the advancement of cybersecurity in a networked world. The integration of knowledge within these scientific domains into a systems perspective is also proving to be a source of novel methodological problems, such as that of knowledge representation in multi-scale, multi-physics contexts.

Pushing the frontiers of research, as is done at ISR, requires continual attention to the invention and exploitation of new methods.

2. Is the strategic plan forward looking, and does it address important national needs?

Yes. See the strategy section on page 3.

3. Does ISR have adequate resources and support from administration to implement the strategic plan?

For many years, ISR could count on a significant commitment at the highest levels of the university, especially in allowing us to maintain independence and a separate core budget. However, in ISR's 25 years there have been four periods of significant cuts in state funding on account of the economy. In recent years, and especially given the deep recession in the latter part of this decade, ISR has seen no additions, and several reductions, to its base budget. In addition, like many parts of the university, ISR has been asked to sacrifice in the forms of givebacks from its budget, having staff lines cut, staff layoffs, furloughs for both faculty and staff, and an absence of both COLA and merit pay increases. The percentage cuts to ISR have been higher than to other units in the A. James Clark School of Engineering.

In the past year ISR has been grateful for the Clark School's recognition of the importance of our new research initiatives and strategy for the future. ISR received start-up funds from Dean Darryll Pines as well as soft money for our new initiatives and the expansion of existing research in systems engineering. Furthermore, the college committed to hiring a director for systems engineering education based on these new directions.

4. What drove ISR in taking a proactive approach to expanding into new areas of research beyond its initial mandate?

There were two primary drivers. The first was scientific curiosity. The world was changing, and ISR took on new areas of research that appealed to our faculty. For example, over the years, materials science became more important, MEMS science and technology was created, and ISR stepped into these areas.

The second driver had to do with progress in engineering. Over the years a broader spectrum of applications has developed. Emerging areas are in need of systems research. We also realized funding resources went along with these new areas, many of which were Department of Defense interests that came to the fore after 9-11.

5. What novel methods has ISR used to organize its research programs?

One method ISR uses is a **federation of centers** organizational model in which programs embody integrated systems research approaches, some aligned more toward application areas and others toward advancing fundamentals in systems research. These centers, housed within and aligned to ISR, share ISR's resources. Some centers are fairly short term, lasting only as long as a specific research grant, while others persist for a longer period of time, pursuing multiple funding opportunities. Examples of centers include the Hybrid Networks Center, NEXTOR, the Center for Auditory and Acoustic Research, and the recently created Maryland

Robotics Center. More detail about these centers appears later in the report.

The federation of centers idea developed during the term of former Director Gary Rubloff, who later used the same concept when he founded the Maryland NanoCenter at the university.

ISR's **Strategic Advisory Council** meets approximately once a year and brings an outside perspective to our research and education programs. Composed of leaders from industry, academia, and government labs in ISR's specific research fields, the SAC makes recommendations to ISR on specific research areas, strategic directions and management concepts.

During Eyad Abed's tenure as director, ISR periodically made available **seed grant funding** to its faculty from its Strategic Investment Fund. The Strategic Investment Fund is funded primarily through the investments of ISR's industrial partners. Seed grant funding was made available when finances allowed; the purpose was to provide start-up money for innovative faculty ideas with multidisciplinary merit. These concepts were developed to the point where proposals for major agency funding could be submitted. Faculty submitted proposals in competition, and one or two grants were selected in each round.

The most recent round of seed grants awarded was in 2009. The projects funded at that time were "An Ornithopter with Enhanced Maneuverability," to Sarah Bergbreiter and S.K. Gupta (both ISR joint appointments with Mechanical Engineering); and "A TNT Optical Microsensor Using a Tobacco Mosaic Virus-Structured Receptor Layer," to Reza Ghodssi and Jim Culver (Institute for Bioscience and Biotechnology and professor in the Department of Plant Science and Landscape Architecture).

In previous years, the cell-based sensor efforts of Pamela Abshire (ISR joint appointment with Electrical and Computer Engineering), Ben Shapiro (ISR joint appointment with Bioengineering) and affiliate faculty member Elisabeth Smela (Mechanical Engineering) were funded; this helped to jump-start a research area that has since proven very fruitful for the trio. In addition, ISR faculty Michael Fu, Dana Nau and Steve Marcus met Rance Cleaveland through a seed grant. Cleaveland has since joined ISR as a joint appointment with Computer Science, and the research begun under the seed grant has led to Marcus and Cleaveland's working together on a large NSF Expeditions in Computing grant.

In addition to these methods, ISR also makes use of retreats, topical workshops, colloquia, and interdisciplinary discussions to shape its research programs. The most recent of these was the Green Communications Workshop, sponsored by ISR and held Oct. 14–15, 2010 at the university. Close to 100 industry, government and academic researchers in this area met to help define a research agenda for this developing field; the agenda will help ISR map a place for its research specialties among funding opportunities under consideration.

E. Industry/Practitioner Collaboration and Technology Transfer

Through the years, ISR has been successful in partnering with industry and other external organizations on many topics of joint interest, using a variety of mechanisms to allow and provide support for the collaborations. ISR has reported many of these successes to NSF, and also publicly disseminated the information. This section of the report highlights several examples and impacts of our successful collaborations with industry, our alumni activities, our international collaborations, technology and IP that is in the commercial sector, as well as perspective on our external relations activities moving into the future.

Our external relations strategy is based on developing research partnerships with external organizations. The foundation for this is building relationships, which provides the basis for collaborations.

ISR offers mutually beneficial partnership opportunities and a one-stop gateway to working with the University of Maryland. These mechanisms include an industrial affiliates program for strategic partners with research collaborations; visiting scholars (industry professionals working on campus with ISR faculty on mutually beneficial research topics for an extended period of time); industry-sponsored research; intellectual property licensing; teaming to win agency-sponsored programs; Maryland Industrial Partnerships (MIPS) for local, small, and start-up companies; ISR students and postdoctoral researchers for permanent hiring; student internships and fellowships; gifts to ISR of cash and in-kind support; and international research agreements.

Engaging with a broad and diverse external community of researchers strongly stimulates innovation. The variety of perspectives and expertise brings fresh ideas on approaching problems and needs, generating innovative solutions, and driving advances in both systems science and systems engineering.

The external relations unit has actively developed programs and formalized methods to facilitate relationships and collaborations with external organizations. These have influenced other university programs and practices, and "institutionalized" visiting scientist procedures, the University Export Control formal process, the standard strategic partners program agreement and process, and international collaboration agreements.

ISR draws upon the university's significant technology commercialization and entrepreneurship resources, led by programs in the Clark School's Maryland Technology Enterprise Institute (MTECH), the Office of Technology Commercialization, and the Robert H. Smith School of Business's Dingman Center for Entrepreneurship. These programs help bring new technologies to the marketplace and new economic growth to the region. Programs include State of Maryland matching grants with industry support; venture capital access, a business incubator program; and an entrepreneurship culture, education, and programs.

Industrial participation in ISR research has remained strong throughout our history. On an absolute scale, the number of companies per year has stayed level and funding remains strong. However, our funding has varied significantly over the years. The composition of our industry collaborators has changed in sync with the evolution of our research programs.

In the past decade, faculty and others have noted that industry has become increasingly focused on the short term. Joint projects with industry now tend to have a narrow focus and a short-range research outlook. Current U.S. and worldwide economic conditions and uncertainty have resulted in great caution in spending and hiring by industry.

These trends have been acknowledged by both industry and academia. Norman Augustine, retired chairman and chief executive officer of Lockheed Martin Corp., noted in 2010 that companies continue to cut back on funding research. At the MIT Media Lab 25th anniversary in October 2010, Nicholas Negroponte, founder and chairman emeritus, concurred that industry has become more conservative in its funding.

In addition, ISR's research areas can be a challenge for industry. It has not always been easy for industry to see the benefits of working with us. General methodology does not generate the same kind of industry funding as protocols and specific technologies.

One other factor is that some of the new interdisciplinary areas ISR entered in the last decade, such as neuroscience and microsystems, do not have the same kinds of large, established industries behind them that the institute's original research concentrations had.

Accordingly, ISR collaborations with industry have evolved and grown using mechanisms including corporate-sponsored research, joint research using the leveraging component of third-party funding such as the Maryland Industrial Partnerships program (MIPS), and teaming to win government agency program awards.

Several examples of ISR research collaborations, implementations and impacts, and partnerships with external organizations are included in this section to give you a perspective on ISR achievements. Many more could be cited.

1. What are examples of successful collaborations between ISR and industry, other practitioners (agencies), and what have been the results?

The foremost example of a successful collaboration is John Baras' and ISR's relationship with Hughes Network Systems. The partnership of HyNet, a NASA-funded Center of Excellence within ISR (explained more fully in section G.2.b.) and Hughes Network Systems is an example of creating a new industry and of industry and academia working side by side, providing internships and career development

1995 — First Consumer Satellite Internet Service DirecPC®

1999 — DirecDuo® DIRECTV and DirecPC on One Dish

2001 — DW4000 2-Way Satellite Access

2002 — DW4020 Self-Hosted Gateway

2003 — DW6000 Consumer Self-Hosted Gateway

2005 — DW7000 Enhanced-Performance Advanced-Modem
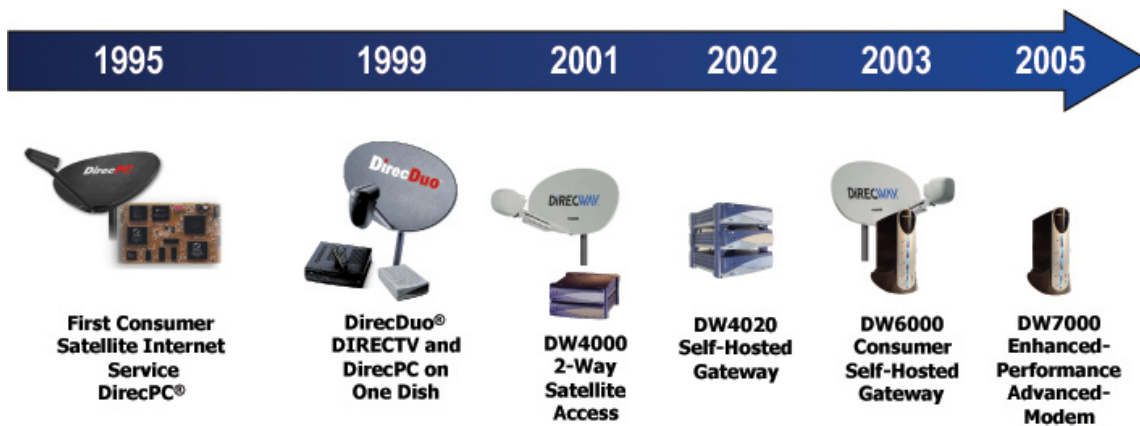
ISR and Hughes Network Systems productization timeline

to students and alumni. Over the years, this work has contributed $8.4 billion in sales to Hughes Network Systems.

This long-term project for hybrid satellite communication systems received basic research support from NASA (NASA Lewis Research Center, NASA Goddard Space Flight Center), the Department of Defense (Army Research Laboratory) and NSF. Maryland state government support came from the Maryland Industrial Partnerships program.

The resulting inventions, DirecPC, Turbo Internet, DirecWay, and SpaceWay, were productized and marketed by Hughes Network Systems.

The inventions received many awards including the University of Maryland 1994 Outstanding Invention of the Year; the Outstanding MIPS Project Award (Large Company Category); Distinguished Engineer of the Year (Doug Dillon, HNS) from the Maryland Academy of Sciences; the ComNet 1996 New Product Achievement Award (wireless category); the 1996 "Hot Product" for network services from *Data Communications* magazine; and the Technical Excellence Award (Networking Hardware category), from *PC Magazine.*

The benefits of the partnership for Hughes Network Systems were access to exceptional students (many of whom were subsequently hired); the chance to work with faculty and research staff of the university; and the creation of new business and approximately 500 new jobs (and expanding) for HNS in Maryland.

Benefits to the University of Maryland included international prominence and leader recognition; a mechanism for attracting the best faculty, research staff and students; and a driver for educational reform.

Benefits to the state and region included: retention of highly qualified people in the area; attracting new and strengthening existing companies; teamwork to improve and enhance the array of HNS commercial products; access to the latest technology and research in satellite and hybrid communication networks; and educated and well-trained professionals for the telecommunications industry.

To date, some 60 students affiliated with HyNet, and many more from University of Maryland at large have been employed by HNS. Each year HNS provides summer internships to HyNet and other students.

Visiting Scholars Program. Toshiba Corporate Manufacturing Engineering Center, Japan, and Honda R&D, Japan, have each partnered with ISR for many years, via ISR's Visiting Scholars Program within our Strategic Partners Program. Toshiba has sent 15 Visiting Scholars to ISR over 10 years of collaborations, and Honda has sent 12 Visiting Scholars to ISR during its nine-year partnership. ISR customizes the visits to meet each corporation's and individual visitor's needs.

These international engineers typically visit for between six and 14 months to complete research projects. Not only do they experience American systems engineering methodologies and applications, but they also become immersed in local culture, language and business practices. Visitors join ISR research teams and use ISR's state-of-the-art tools, working alongside University of Maryland faculty and students. The resulting network of scholars continues to interact over time and become another resource advancing ISR research.

Past collaborations have encompassed a wide range of technical areas. Extensive and frequent discussions and meetings are held to maintain a close relationship and work towards identifying additional collaborations. Importantly, our standard practice is that when an ISR faculty member cannot be identified as the best-match expert in the field, ISR identifies other University of Maryland faculty and brings them into the team for that particular project. This builds the best possible connection between the company and the university.

Toshiba. Toshiba engineers spend an average six months to one year at ISR conducting concentrated cross-disciplinary research with ISR faculty members. This program has produced valuable research results for Toshiba. For example, research with Michael Ball produced supply chain management algorithms that reduced inventory costs and due date violations. This is being implemented in a manufacturing group to reduce lead time, to increase product quantity and

to decrease manufacturing operation time. The research adapted previously published mixed-integer-programming (MIP) models to specific requirements posed by an electronic product supply chain within Toshiba. The model provides individual order delivery quantities and due dates, together with production schedules, for a batch of customer orders that arrive within a predefined interval.

Another example is research with V. S. Subrahmanian which produced data mining algorithms that showed improved manufacturing process performance and efficiency. The joint project established a theoretical background and an improved data mining technique to analyze huge manufacturing databases. Researchers saw the need to identify defect causes, then improved manufacturing yield by reducing them. An algorithm was developed which was tested on a known data set and compared to existing techniques. The new algorithm consistently extracted the correct answer, executed more quickly, and was more robust than existing techniques.

The ability to interconnect multiple chips at different elevations on a single substrate could significantly improve the performance of advanced small optical modules and reduce the package size of a MOSFET relay. In their project, "Compact Packaging Using MEMS-Based 3-D Substrate Interconnects," researchers from Toshiba along with Reza Ghodssi and Gottlieb Oehrlein (Materials and Nuclear Engineering and Institute for Research in Electronics and Applied Physics) developed compact 3-D silicon substrate interconnects. Gray-scale lithography technology was used to create smooth inclined surfaces between multiple vertical levels. Successful electrical interconnection was established via metal evaporation and contact lithography using spray coating. The research also developed processes for through-hole interconnects fabricated using deep reactive ion etching. The research emphasized achieving positively tapered, smooth sidewalls to ease deposition of a seed layer for subsequent Cu electroplating. A joint journal paper was written.

Mr. Satoshi Sumida, Director of Toshiba Corporate Manufacturing Engineering Center, says, "We have partnered with ISR for many years, primarily by sending our engineers who become Visiting Scholars and work as an integral part of a faculty-led research team on topics of mutual interest. Our company and these engineers have benefited greatly from these collaborations."

Honda. ISR's partnership with Honda brings their high-quality and high-promise engineers to ISR to complete a 14-month set of objectives. Honda engineers are paired with ISR faculty on projects suited to their specialties. As part of Honda's globalization effort, the engineers experience U.S. university research culture and also learn English. Past engineers have worked on control theory research; 3-D image reconstruction for video images; hybrid electric vehicle transmissions; and motorcycle noise-damping systems. In addition to the Honda visiting scholars, ISR faculty have been awarded two separate Honda Initiation Grant program awards, which added new mechanisms for our collaborations.

Research with ISR-affiliated faculty member William Levine (Electrical and Computer Engineering) developed an engine idle speed and emission controller that favorably compared to existing controllers. Modeling was used extensively. The engine model included airflow dynamics, combustion, fuel injection and catalytic converter components. A model was developed by linearizing at nominal points. The model's accuracy was evaluated by comparing both measured and simulated data. The models were used to compare idle controllers, air-fuel ratio controllers, and emission controllers.

Research with ISR-affiliated faculty member Yiannis Aloimonos (Computer Science and University of Maryland Institute for Advanced Computer Studies) studied the 3-D reconstruction of an environment from images using a combination of a stereo camera and motion disparities. The researchers considered information important for a variety of tasks in which a vehicle must avoid collision or find an optimal course. In conventional research, the camera or objects in view are stationary. In this project, the goal was to achieve environment understanding in scenes that may contain multiple independently moving objects, while the stereo camera imaging the scene is also moving. Because human vision excels at this problem, knowledge about human visual motion analysis was used as inspiration.

Northrop Grumman Electronic Systems was an ISR industrial affiliate program member for 20 years, mostly as a sustaining partner, our highest level of membership. We typically worked on three or four joint projects per year. Project topic areas were mutually agreed upon based on the expertise of ISR faculty and Northrop Grumman's needs at the time. Other collaborations and benefits included: teaming to win agency program awards, participation on the ISR Strategic Advisory Council, Maryland MIPS (state matching) awards, student hiring, in-kind donations, and cash gift support. Extensive and frequent discussions and meetings were held to maintain a close relationship and work towards identifying additional collaborations.

A recent Northrop Grumman collaboration success involved an ISR research team led by Gary Rubloff and Ray Adomaitis (joint appointment with Chemical and Biomolecular Engineering) that exploited ISR's skills in chemical process sensing, metrology, modeling and simulation, equipment design, and process control.

ISR's contributions are recognized by Northrop Grumman as an important component in its many advances in the field. ISR contributions have helped move Northrop Grumman to a position of competitive leadership in GaN-based materials and process technology for microelectronics systems, in material quality, process uniformity, film thickness control, and manufacturability. Northrop Grumman has used ISR contributions to fabricate high power, high frequency GaN devices. This significant new capability enabled Northrop Grumman Electronic Systems to move from an original Phase I to a considerably larger Phase II Defense Advanced Research Projects Agency (DARPA) program.

ISR has a productive history of collaborations with **Intelligent Automation, Inc.,** (IAI), through a variety of mechanisms led primarily by P. S. Krishnaprasad. IAI's current President, Dr. Vikram Manikonda, is an ISR alumnus, and member of the ISR Strategic Advisory Council. Through gifts from IAI, ISR's Intelligent Servosystems Lab (ISL) has a dedicated license to the commercial multi-agent computation platform Cybelepro, a distributed control framework, and an industrial implementation of MDLe for higher level motion programming.

MDLe is a motion control language for robotics originally developed with the help of Manikonda while he was a graduate student. MDLe continues further development and implementations at ISL and with IAI, which uses MDLe robotic motion control language in its products and services.

Two current IAI research scientists have part-time visiting appointments with ISR, interacting with Tony Ephremides and Michael Fu and their students. The scientists visit campus as their schedules permit and have produced two journal papers and three conference papers. IAI has hired eight ISR alumni as permanent staff members, and periodically hire students as interns.

Jeffrey Herrmann (joint appointment with Mechanical Engineering) created the **Clinic Planning Model Generator** (CPMG), an emergency preparedness planner, which is used in state and county public health departments across the U.S. to design more efficient emergency dispensing clinics. CPMG is a spreadsheet application that generates customized analytical models of mass dispensing and vaccination clinics. The various software programs—CPMG, the Vaccine Allocation Model, and eMedCheck—are available online for free download to personal computers and handheld devices. The funding for developing and testing CPMG software was provided through the Montgomery County, Maryland, Advanced Practice Center for Public Health Emergency Preparedness and Response; by an award from the Centers for Disease Control and Prevention (CDC); and the National Association of County and City Health Officials (NACCHO).

Herrmann was one of 24 winners statewide of the *Maryland Daily Record's* Innovator of the Year awards in 2008. His CPMG work plays an important role in guidance issued by the CDC. The document requires that agencies receiving funding under a federal agreement use Herrmann's CPMG software as the model to help meet CDC's "preparedness control goal for mass prophylaxis."

Robert Hoffman (Math Ph.D. 1997), a manager at **Metron Aviation,** has a long-running ISR visiting appointment to conduct research on NEXTOR's Collaborative Decision-Making (CDM) project with his former advisor Michael Ball. Significant FAA and NASA funding has resulted from the Metron-ISR partnership. Working with Metron, ISR research results have been integrated as new features into Flight Schedule Monitor, the FAA collaborative decision making support tool for planning and controlling ground delay programs. Also, with Metron ISR has performed data

analysis that has improved FAA decision making both in policy and in decisions on new tools and operational procedures. Metron has hired three ISR students, and six joint papers have resulted.

2. Who are some of ISR's key alumni, and what do they do now? What are some examples of benefits to external organizations that have hired ISR alumni?

A select list of ISR alumni by research area and their current places of employment is included in the appendix to this report. Below are comments from some of our alumni about ISR's benefits to them and how these benefits accrue to their current employers.

As mentioned previously, **Vikram Manikonda** is the president of Intelligent Automation, Inc., a company that has hired many ISR alumni. Manikonda earned his Ph.D. in electrical engineering in 1997, advised by P. S. Krishnaprasad. He says, "I benefitted firsthand from ISR's interdisciplinary environment and close research ties with industrial partners during my term as an Electrical and Computer Engineering Ph.D. student. Today, as a leader of an organization focused on applied R&D, I take advantage of continuing research, internship and hiring opportunities with ISR to bring value and benefits to our company."

Mounya Elhilali is an assistant professor at Johns Hopkins University. She earned a Ph.D. in electrical engineering in 2004, advised by Shihab Shamma (ISR joint appointment with Electrical and Computer Engineering). She also was an ISR postdoctoral researcher after graduation. Elhilali won an NSF CAREER Award in 2009 for "Cognitive Auditory Systems for Processing of Complex Acoustic Scenes." She writes, "The opportunity to interact among multiple disciplines was key. My home department was Electrical and Computer Engineering, but a lot of my work was at the interface of neuroscience and engineering. Being part of ISR gave me the opportunity to interact with people in other disciplines, particularly in biology and neuromorphic engineering. The opportunities that were offered through ISR for interdisciplinary interactions made the difference in the direction my research took, and that influence continues in what I am doing now."

Stefano Coraluppi currently is a senior scientist at Compunetix, previously working for Alphatech (BAE Systems) and the NATO Undersea Research Center. He earned a Ph.D. in Electrical and Computer Engineering in 1997, advised by Steve Marcus. Coraluppi writes, "The systems focus at ISR enabled me to progress effectively at Alphatech and NATO, as well as in my current position. I am able to work productively with researchers who have backgrounds in other areas of engineering, computer science, physics, and mathematics. My area of work is inherently cross-disciplinary, and as such ISR background is valuable. I have worked extensively in both industry and government, and interface constantly with academia."

Brian Morgan is an electronics engineer at the U.S. Army Research Laboratory. He earned a Ph.D. in electrical engineering in 2006, advised by Reza Ghodssi. Morgan writes: "The biggest benefit of being associated with ISR was that it got me out of my research bubble. It forced me to look at the big picture and not see everything as an electrical engineering problem. Today, in forming and managing my team, I value assembling people with multiple backgrounds to work on a particular problem. This forces everyone to present their work to audiences outside their immediate field. Diverse audiences are usually when we get the best feedback."

Rajiv Laroia, (Electrical Engineering Ph.D. 1992, advised by current Provost Nariman Farvardin), is a leading developer of wireline and wireless technologies. He sold his company Flarion Technologies to communications giant Qualcomm several years ago. His signal processing algorithms helped to double the speed of data over landline modems and will allow companies to bring enhanced internet functions to mobile phones. Farvardin and Laroia, along with Steven Tretter (Electrical and Computer Engineering) received U.S. Patent 5,388,124 in 1995 for "Precoding Scheme for Transmitting Data Using Optimally-Shaped Constellations Over Intersymbol-Interference Channels." Laroia has continued working with ISR faculty through the years, including M. Scott Corson (now with Qualcomm), with whom he shares U.S. Patents 7,069,000 and 7,016,690. He was inducted into the A. James Clark School of Engineering's Innovation Hall of Fame in 2006.

Naomi Leonard (Electrical Engineering Ph.D. 1994, advised by P. S. Krishnaprasad) is the Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering at Princeton University. Leonard is an IEEE Fellow for her contributions to control of underwater vehicles. She won a MacArthur Fellow "genius grant" in 2004. Leonard has also received the University of California at Santa Barbara Mohammed Dahleh Distinguished Lecture Award (2005), the Automatica Prize Paper award (1999), the Office of Naval Research Young Investigator Award (1998) and the National Science Foundation CAREER Award (1995). She has delivered several plenary lectures at conferences including the American Control Conference in 2010, the Canadian Mathematical Society Winter Meeting in 2009, the IEEE International Conference on Robotics and Automation (ICRA) in 2008, the International Symposium on Mathematical Theory of Networks and Systems (MTNS) in 2008, the IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles in 2008, the SIAM Conference on Control and Its Applications in 2005, the SIAM Conference on Applications of Dynamical Systems in 2003 and the IFAC Nonlinear Control Systems Design Symposium (NOLCOS) in 1998.

3. How has ISR established and used international partnerships?

International collaborations allow ISR to establish research teams of the best and brightest researchers worldwide, bringing additional expertise, issues, perspective, and re-

sources to research challenges. These collaborations provide a "global perspective" to our faculty and students, from both a research and a cultural perspective. We have a strong bidirectional visitors program where researchers freely travel and spend extended time at each other's locations. Most of these partnerships develop because of current or past relationships. ISR has 10 formal agreements with international organizations, and is developing several more.

The Center for Wireless Communications at the University of Oulu, Finland, has hired Anna Pantelidou (2009 Electrical and Communications Ph.D., advised by Tony Ephremides) as a postdoctoral researcher.

Other international collaborations include joint papers, joint funding, and proposals. We regularly offer and participate in bi-directional, short-term visits by researchers, as well as invite and provide speakers at international conferences and events. ISR also is making plans for short course development and teaching and plans for joint graduate degrees.

ISR has international representation on our Strategic Advisory Council. Once again, this brings a unique perspective and the best and brightest together to provide guidance and constructive criticism to ISR.

4. What are some of the major technologies and intellectual property that ISR has produced and transferred to industry, research labs, agencies, etc.? What has been their impact on products, processes or services?

Ben Shneiderman's Spotfire product developed in the ISR-affiliated Human Computer Interaction Lab is used by most pharmaceutical companies for drug discovery and genomic data analysis, and is increasingly adopted for business intelligence analysis for oil and gas discovery, manufacturing control, marketing, supply chain management, and financial analysis. Spotfire is a starfield multidimensional data visualization display tool using dynamic queries. Christopher Ahlberg, a visiting student from Sweden at the time, worked under the guidance of Shneiderman to lead the development of Spotfire. He started and was CEO of a company (also called Spotfire) that grew to 200 employees, and was purchased by Tibco in 2007.

Ben Shneiderman and his research team in HCIL developed Treemaps, a space-filling method of visualizing large hierarchical collections of quantitative data. Treemaps gives users the ability to see thousands of data bits in a fixed space that facilitates discovery of patterns, clusters and outliers. Treemaps is in use in a variety of commercial applications. SmartMoney.com uses Treemaps technology in its Map of the Market, which tracks the performance of several hundred stocks across various sectors. Marumushi.com's Newsmap (newsmap.jp) shows the relative amount of coverage of major news stories in various countries around the world.

Carol Espy-Wilson has been honored as a 2010 Maryland Innovator of the Year for "Multi-Pitch Tracking in Adverse Environments," her invention that radically improves sound quality over cell phones and in hearing aids, among other devices. This technology is behind Espy-Wilson's Omnispeech LLC company. Previous technologies work by taking in all of a sound, then attempting to filter out anything that is not speech. Espy-Wilson's innovation is a technology that pulls the speech out of the noise by focusing on the characteristics that make speech unique. Espy-Wilson founded Omnispeech LLC in 2003 to bring the technology to market and is the company's chief technology officer. Omnispeech won the high tech category in the 2010 University of Maryland $75K Business Plan Competition and is currently in the university's Venture Accelerator program. A prototype on an industrial communications device is being demonstrated. Espy-Wilson and her Ph.D. student Srikanth Vishnubhotla also won the 2009 University of Maryland Invention of the Year award in the Information Science category for this technology.

André Tits has expertise in various aspects of numerical optimization, optimization-based system design and robust control with emphasis on numerical methods. His research group has developed several software packages implementing these algorithms, notably CONSOL (a tool for interactive optimization-based design of a large class of systems) and FSQP (feasible sequential quadratic programming source code tools for constrained nonlinear optimization). AEM Design Inc. licenses these for the university. FSQP is in use at more than 1,000 locations around the world.

Eyad Abed and his research group have introduced a nonlinear control design which permits the operation of an axial flow compressor up to and beyond the stall limit. This research provides a key step toward the integrated control of jet engine aerodynamic and combustion instabilities, leading to lighter engines with greater improved performance characteristics for use in future military and civilian aircraft. The work was advanced and implemented in a major experimental setup at United Technologies Research Center, and was funded under an AFOSR grant.

A research team lead by **Dana Nau** developed an advanced artificial intelligence (AI) planning technique for generating and evaluating bridge-playing strategies. This technique was incorporated into an existing commercial product, Bridge Baron, at Great Games Products. Bridge Baron is a computer program for declarer-play bridge. It won the 1997 world championship of computer bridge. A generalization of the technique is useful in problems as diverse as manufacturing planning and emergency evacuation planning.

Raghu Raghavan (ISR joint appointment with the Robert H. Smith School of Business) and his former student Ioannis Gamvros won the European Association of Operational Research Societies' (EURO) 2010 Management Science Strategic Innovation Prize for their jointly authored paper, "Multi-Period Traffic Routing in Satellite Networks." The paper deals with a strategic multi-period demand routing problem in satellite networks that has strong implications for revenue management. It develops

an elegant mathematical approach to successfully solve this problem, which has been estimated by the satellite provider to potentially save several hundred million dollars.

5. What has been ISR's impact on industrial/practitioner practice and the creation of new industrial sectors?

ISR alumnus **Buno Pati** (Electrical Engineering Ph.D. 1992, advised by P. S. Krishnaprasad) is a member of the A. James Clark School of Engineering's Innovation Hall of Fame for his innovations in phase-shift lithography, which have driven the development of ever-smaller electronic devices with ever-expanding applications. Pati's work has improved the capabilities of computers, cell phones, GPS devices and MP3 players. Pati is an experienced and successful entrepreneur who has an established track record of building numerous early-stage companies into successful businesses.

Currently, he and Phil Wiser (Electrical Engineering B.S. '90) run Sezmi, which creates products designed to change the TV viewing experience by bringing together in one "network" all the sources of video content available today, including the Internet. Sezmi makes it easy to manage those sources in a personalized, yet automated way.

Pati has been an angel investor, board member and on occasion, interim chief executive officer of early-stage venture-funded technology companies in a range of markets from semiconductors to video compression and multimedia services. Pati founded Numerical Technologies, which "productized" phase-shift technology, and served as its president and chief executive officer. He led the company from the initial development phases through its successful initial public offering to its acquisition by Synopsys.

FlexEl LLC is commercializing a flexible, ultra-thin battery with a thickness comparable to a business card. The batteries have higher storage capacity than any other battery available today, are non-toxic, and can be recharged wirelessly. ISR-affiliated faculty member Neil Goldsman (Electrical and Computer Engineering), along with Electrical and Computer Engineering faculty member Martin Peckerar and research associate Zeynep Dilli, developed the company's patent-pending technologies. FlexEl has won awards including being named company of the year in the technology transfer category at the 2010 Maryland Incubator Company of the Year Awards; the University of Maryland's Invention of the Year award in 2008; and the high-technology category of the University of Maryland's $75K Business Plan Competition in 2009. Goldsman received $75,000 from TEDCO's Maryland Technology Transfer and Commercialization Fund to further the work; and is a participant in the University of Maryland Technology Enterprise Institute's (Mtech) Technology Advancement Program (TAP) incubator.

Resensys LLC develops self-powered, energy-harvesting, wireless, distributed sensors for persistently monitoring structures such as bridges, buildings, and pipelines. The

company's patent-pending technology was invented by ISR alumnus Mehdi Kalantari (Electrical and Computer Engineering Ph.D. 2005, advised by ISR-affiliated faculty member Mark Shayman). It detects strain, deformation, and cracks forming in structures, and provides early warnings when problems arise. Resensys sensors are easy to install on existing structures, are ultra-energy-efficient, and are environmentally friendly. Resensys won the high tech category in the 2008 University of Maryland $50K Business Plan Competition and graduated from the university's Venture Accelerator to the Technology Advancement Program (TAP) in March 2010. Under a pilot program agreement with the Maryland State Highway Administration, Resensys has installed six sensors that monitor conditions on a 50-year-old bridge along the Washington D.C. Capital Beltway.

6. How well do the new areas align with industry/practitioner needs in the near future?

In the last year, under the leadership of Director Reza Ghodssi, ISR has identified **three new research initiatives** in robotics, green communications and microsystems, and is significantly enhancing research and education programs. ISR is providing a focus and a home for formerly separate and extensive research in robotics and microsystems that has been occurring on campus for some time. In addition, ISR is leading efforts in the relatively new research field of green communications. The establishment of these initiatives will build a strong and collegial atmosphere in ISR and the university for faculty, researchers, and students to interact with each other. This will help formulate and identify some of the future grand challenges for each initiative, producing a high societal impact. The robotics and green communications initiatives are already strongly engaging with industry, government agencies, and other research institutions as they identify and define their focal activities. There is very strong alignment with the external community for these initiatives.

The year-old **robotics initiative** already has resulted in the formation of the Maryland Robotics Center, approved by the A. James Clark School of Engineering and housed within ISR. The center recently held an extremely successful "Maryland Robotics Day" open house event with more than 400 industry representatives, government researchers, academics and K-12 students learning about our expertise and seeking opportunities for collaboration. This event also drew strong coverage from local television stations, science reporters, and the Voice of America.

Maxim Schwartz, a software engineer at Energetics Technology Center, is working closely with Maryland Robotics Center Director S.K. Gupta, on developing an **unmanned boat** with funding from the Office of Naval Research. Schwartz and Petr Svec, a University of Maryland postdoctoral researcher, showed open house visitors a simulation that demonstrates how an unmanned boat can intercept an attacker and block its movement. The simulation software

lets the robot react in different situations, such as predicting the maneuvers a pirate speedboat might take to reach a protected target.

The White House's FY 2012 Science and Technology Priorities Memo, notes federal agencies should focus resources on addressing six challenges, including "promoting sustainable economic growth and job creation." One way of doing this is through the support of research and development in advanced manufacturing to strengthen U.S. leadership in the areas of robotics, cyber-physical systems, and flexible manufacturing.

From Oct. 14–15 of this year, ISR's **green communications initiative** led by Anthony Ephremides held a workshop to define the critical issues requiring research attention. Close to 100 representatives from industry, government and academia attended. In addition, the University of Maryland, through ISR, has become a member of the GreenTouch Consortium, a worldwide group of leading industry players, research institutions and non-governmental organizations. Consortium members work together to define challenges and identify and develop solutions. The goal is to deliver within five years the architecture, specifications, roadmap, and demonstrations of key components needed to increase information and communications technology (ICT) network energy efficiency by a factor of 1,000 from current levels.

As described in other sections of this report, ISR's **research and education programs** recently have undergone significant enhancements. Faculty have strongly engaged with external organizations as we move forward with both joint research activities and educational programs for senior administration and staff members. ISR has ongoing specific collaborations and more developing through a CRADA agreement with the Army at Aberdeen, Md., where Base Relocation and Closing (BRAC) activity is bringing several thousand Department of Defense employees to Maryland. This, combined with a concurrent strong increasing emphasis for systems engineering research and education in government programs (DoD UARC Systems Engineering Research Center, DDR&E, Army RDECOM, and Air Force), has provided a great opportunity for ISR to partner and serve these needs. We are engaging with Lockheed Martin, NIST, and Pratt & Whitney Rocketdyne to leverage each other's interests, needs and resources, to the benefit of all participants.

The first 50 years of the 21st century will be dominated by advances in methods and tools for the synthesis of complex engineered systems to meet specifications in an adaptive manner. This is evident from the areas emphasized by governments, industry and funding agencies worldwide: energy and smart grids, environment and sustainability, biotechnology, intelligent buildings and cars, systems biology, customizable health care, nanotechnology, pharmaceutical manufacturing innovation, the new Internet, broadband wireless networks, collaborative robotics, sensor networks, software critical systems, transportation systems, homeland security, security-privacy-authentication in wireless networks,

materials design at the submolecular level, cyber-physical systems, network science, web-based social and economic networks.

We frequently encounter the descriptive term, "system of systems." Complexity manifests itself through heterogeneity of subsystems and components. The synthesis of complex engineered and other systems form components so as to meet specifications. The associated education represents the next frontier in engineering research and education. It is the frontier that will determine the next generation leaders among universities and industry.

F. Systems engineering education

Through the years, ISR's comprehensive education program has included high school students through postdoctoral researchers. These programs have had a profound effect on the engineering education provided by the University of Maryland and their influence has spread well beyond the campus.

1. ISR had a strong program in pre-college and community college educational outreach under ERC Program support. Was that sustained?

For several years in the early 1990s, ISR hosted an NSF **Young Scholars** program. Each summer, up to 25 pre-senior high school students spent six weeks at ISR, where they took ENES 100 (Introduction to Engineering Design) and earned three credits. Students also spent several afternoons each week in an ISR-affiliated lab and attended a wide array of seminars, field trips, and workshops. This program was extremely successful and was praised by students, parents, and teachers.

Followup with students in the mid-1990s indicated that more than 60 percent went on to pursue degrees in engineering or science, many at the University of Maryland. ISR continued to offer Young Scholars until NSF changed the program. The university still operates a Young Scholars Program in several academic disciplines. Those participating in the engineering program continue to take the ENES 100 course, and ISR faculty such as David Lovell (ISR joint appointment with Civil and Environmental Engineering) continue to teach in this program, as recently as summer 2010.

2. What are ISR's most significant achievements in education?

Graduate education. ISR's most substantial effects on engineering education have come at the graduate level, especially because of the interdisciplinary nature of ISR's faculty and research. With faculty and students dispersed over 11 departments and four colleges on campus, the breadth of expertise and methodologies that ISR brings to systems-related problems are unique. In addition, the concept of ISR as a "home"—with faculty and students from different departments sharing offices and laboratories—has created a unique environment that has had a significant effect in expanding the horizons of ISR graduates. This has already been mentioned by our alumni in questions C.4 and E.2.

ISR established the **Master of Science in Systems Engineering (MSSE)** in 1986–87; it represented the first multi-college graduate degree program at the University of Maryland involving the A. James Clark School of Engineering. From 1994-1998, with input from industry and many case studies, ISR transitioned to more systematic development of the new and quantitative systems engineering curriculum. From 1999-2002, with support from an NSF Research and Curriculum Development grant and from industry, ISR developed and taught three new and very strong courses on the foundations of systems engineering: System Modeling; System Requirements and Tradeoff Analysis; and System Validation, Verification and Testing. From 2006-2007, the MSSE was again restructured with help from industry.

The MSSE program differs qualitatively from other engineering degrees. While traditional disciplines concentrate on the generation and use of knowledge within a specific domain (e.g., electrical circuits, materials, robotics), systems engineering finds its focus in the team-based design, analysis, and integration for problems involving multiple disciplines (e.g., electrical, mechanical, software, human-machine interfaces). Real-world engineering projects typically require the systems-level cooperation of experts from several engineering disciplines. Systems-level considerations are recognized as being paramount in the design of new products.

The goals of the MSSE program are to provide broad exposure to a wide range of systems engineering principles, including software tools for modeling and optimization, decision and risk analysis, stochastic analysis and human factors engineering; familiarization with financial and management issues associated with complex engineering systems; and a deep understanding of one particular application area.

The graduate program has been maintained in several forms: the MSSE (with thesis or scholarly paper requirement), and the corresponding **Professional Master's degree—Systems Option** (ENPM; courses only, no thesis). The Office of Advanced Engineering Education also offers a certificate program in Systems Engineering (four courses required), which students can transfer into a full Master of Engineering degree. Rising demand for systems engineering education continues to provide a strong incentive for efforts to revise, improve, and disseminate these unique programs. Many students in other engineering disciplines often take systems engineering core courses to complement their degree programs. To broadly expand our ability to offer systems engineering education, courses are offered via the university's Distance Education Technology Services, which provides live video to locations across the state.

Postgraduate education. ISR hosts a large number of U.S. and international postdoctoral researchers, who are exposed to unique opportunities and a rich research envi-

ronment, and are substantial contributors to our research program. While ISR welcomes applications from qualified individuals in systems, control, and communications, each year we focus on and announce our search for specific research projects. The number of postdoctoral researchers working at ISR has grown as ISR has matured. Through the years, ISR has hosted 154 postdoctoral researchers. Fifteen postdoctoral researchers are currently working on research projects.

Undergraduate education. For many years ISR faculty have played a significant role in exposing undergraduates to research and influencing the undergraduate curriculum, including the freshman engineering design course and the senior-level "walking machines" course. Many students have taken "projects" courses during which they worked on research and development tasks under the guidance of ISR faculty and graduate students.

Undergraduate research consistently has been supported since 1987 through NSF **Research Experience for Undergraduates** (REU) programs. REU programs offer stipends to undergraduates from other universities, as well as from the University of Maryland, to work on research projects at ISR during the summer.

While ISR has not had REU programs every summer, we have had a number of REU programs in the last 25 years. Our most recent REU program was offered from 2003–2008, under the direction of S.K. Gupta. In addition, since the last REU program ended, three faculty have submitted REU site proposals, including two during the current request for proposal period, for which decisions have not been made.

ISR was chosen to administer the brand-new **Gemstone** program in 1996. The innovative, interdisciplinary undergraduate honors program was conceived by former A. James Clark School of Engineering Dean William Destler (now president of the Rochester Institute of Technology). As the Clark School's first interdisciplinary unit, ISR was the natural incubator for this unique undergraduate education program. Freshmen in Gemstone form teams and spend the next three years analyzing and investigating important societal problems from various disciplinary perspectives. Two ISR faculty members, Thomas Fuja (now at the University of Notre Dame) and Christopher Davis (Electrical and Computer Engineering), have served as the director of the Gemstone program and many others have served as Gemstone team mentors. Currently, four ISR faculty are mentoring Gemstone research teams: Jeffrey Herrmann (Bioweapon Inhibition team), ISR-affiliated faculty member Bruce Jacob from Electrical and Computer Engineering (Dietary Information and Evaluation Technologies team), Ray Adomaitis (Light Energy in the Agriculture of the Future team), and ISR-affiliated faculty member Yiannis Aloimonis from Computer Science (Analyzing Movement of Infants at Risk for Autism Spectrum Disorder team). Oversight of the Gemstone Program remained in the A. James Clark School of Engineering until it became one of the five living-learning programs within the University's Honors College in July 2010.

While the Gemstone Program captured tremendous attention across the campus and throughout higher education, it also stimulated thinking within ISR about mechanisms to bring systems educational experiences to undergraduates. A recent example of ISR faculty influence in undergraduate education is Jeffrey Herrmann's service as the associate director for the university's **Quality Enhancement Systems and Teams** (QUEST) Honors Fellows Program. QUEST is a unique three-year undergraduate experience that includes exceptional students from the A. James Clark School of Engineering, the Robert H. Smith School of Business, and the College of Computer, Mathematical and Natural Sciences. The program offers special courses and experiences that focus on cross-functional collaboration, quantitative methods, interactive planning and quality principles. QUEST collaborates with professional partners who enable student interaction with real-world applications of quality approaches, tools and methods learned in the program courses.

In addition, ISR faculty are also involved in humanitarian efforts with high undergraduate participation. David Lovell serves as the faculty advisor of the Clark School's chapter of **Engineers Without Borders** (EWB). EWB is a student-run, non-profit humanitarian organization dedicated to sustainable development through engineering assistance and training internationally responsible engineering students. The organization partners with communities around the world to design and implement engineering solutions. Lovell has supervised EWB projects in Burkina Faso, Ethiopia, and the Pine Ridge Indian Reservation in South Dakota.

Summary of Achievements. Collectively, these programs have had a profound effect on the engineering education provided by the University of Maryland. Their influence has spread well beyond the campus. Students influenced by ISR have freely interacted with a larger community of students who are working toward degrees in their home departments. It is important to remember that the time a student spends with ISR is only one step in a chain of educational experiences. Many of our best students in the 1985–2000 period now occupy senior faculty positions at prestigious universities or have risen in the ranks of large, well-known corporations.

3. What has been ISR's impact in producing a new generation of systems engineers, and what are the special characteristics of its graduates?

Oddly enough, ISR's best days in educating a new generation of systems engineers may still be ahead of us. In the mid-1980s, the systems engineering profession was very immature and stuck in a document-centric mindset. This disconnect caused a number of problems in our interactions and efforts to form cooperative working relationships with industry. ISR was created in part to develop formal model-based approaches to systems analysis and systems engineering. It is fair to say that in retrospect, ISR was ahead—perhaps even far ahead—of its time.

Twenty-five years later, the computing industry has evolved through remarkable advances, and the profession is moving swiftly toward the development and adoption of model-based systems engineering procedures. During the post-NSF funding era ISR has realigned the goals of the MSSE program and associated research efforts to meet the current and future needs of U.S. industry.

With NSF CRCD funding ISR completely redesigned and re-implemented our systems engineering core courses. Our students really appreciate this change. Also, during the past 25 years, the overall interest and importance of systems engineering has grown exponentially. The National Council for Systems Engineering (NCOSE) was formed in 1990; now INCOSE (its international counterpart) contains almost 10,000 members. One key measure of the growing importance of systems engineering can be found in strategic relationships now being formed between industry and academia, and the very large numbers of students now seeking formal systems engineering education.

ISR is currently moving forward on two fronts. First, in May 2010, John Baras and Mark Austin (joint appointment with Civil and Environmental Engineering and ISR's graduate program director of systems engineering), were awarded a contract from the Systems Engineering Research Center (a consortium of 19 universities funded by the Department of Defense) to develop a **pilot capstone course in hands-on systems engineering projects** for senior-level undergraduates across all areas of engineering. The goal is to expose undergraduate and graduate-level students to the exciting opportunities in the systems engineering profession and the technical aspects of systems engineering through team-based project development.

This project is an experiment in the sense that it is not clear how systems engineering education for undergraduates should differ from approaches followed at the graduate level. The course was offered for the first time in Fall 2010 and will be repeated in Spring 2011. For the 2010-2011 academic year, project work is driven by three product development projects provided by the Army Research Laboratory and Aberdeen Proving Ground: (1) a black box for army transport vehicles, (2) the integrated security of wireless sensor networks, and (3) an integrated vehicle bus architected for army transport vehicles.

This pilot capstone course is taking full advantage of the University's proximity to Washington D.C. and the high number of systems engineering experts in our area. These experts from military, commercial, and government arenas will be invited to share their professional expertise and excitement for systems engineering. We expect that these presentations will be attended by every pilot capstone student and graduate-level MSSE student, and by faculty and students throughout the Clark School.

Second, in September 2010, the University of Maryland signed a **Cooperative Research and Development Agreement** (CRADA) with the U.S. Army Research, Development and Engineering Command (RDECOM). The principal RDECOM lab and center for this CRADA is at the Aberdeen Proving Ground. The CRADA agreement establishes cooperative efforts between the university and RDECOM for systems engineering research and development. ISR is leading the CRADA responsibilities within the university; John Baras is the principal investigator. ISR expects to initially provide systems engineering short courses to high-level personnel at the Aberdeen Proving Ground, which will be followed by military personnel applying for Master's degrees in Systems Engineering at the University of Maryland. Aberdeen tentatively estimates that 1,700 students will need education in systems engineering.

4. What impact has ISR's systems engineering education program had in catalyzing similar programs elsewhere?

As noted above, ISR's focus in systems engineering education has fundamentally differed from most systems engineering programs in the country. However, as model-based systems engineering procedures mature, and as we move to align ourselves with industry needs, this gap will no doubt close. In terms of "catalyzing other programs," our best days in systems engineering are still ahead of us.

5. What is the value of ISR to students?

As is evident from the comments of our alumni in sections C.4 and E.2, being associated with ISR has had a long-lasting impact on our students. Following are several additional points about ISR student culture.

In the early days, particularly the first 10 years of ISR, faculty and staff worked very hard to foster a community spirit among the students. Students were invited to ISR-hosted presentations and distinguished lectures, and were encouraged to attend talks and workshops outside their specific area of interest to enrich their educational experience and expand their exposure to research. ISR hosted an afternoon "coffee break," many social events, and weekend excursions such as camping and canoe trips. Fifteen years later, some of our early students visit and give talks. It is clear these early efforts paved the way for lifelong friendships.

When Reza Ghodssi assumed the ISR directorship in Fall 2009, he wanted to re-energize student culture and interaction and re-develop students' sense of belonging within ISR. ISR faculty were asked to nominate enthusiastic students to serve as the initial leaders of an **ISR student organization**. These student leaders develop and plan activities such as a "new student" welcome, seminars by ISR alumni, industrial partners, faculty, and student trips and gatherings.

G. Infrastructure

1. Leadership and Team

a. How has the leadership evolved over time and what are the lessons learned for Maryland and other ERCs?

The ISR director is an administrative position equivalent to a department chair. The director is chosen in the same way as a chair: a careful search process, a committee and the same expectations of quality. Like chairs, directors serve five-year renewable terms. ISR's directors have been John Baras (1985–1991), Steve Marcus (1991–1996), Gary Rubloff (1996–2001), Eyad Abed (2001–2009), and Reza Ghodssi (2009–present).

To be successful, the ISR director needs to be surrounded by strong, supportive faculty and administrative staff and must be able to gain a consensus about the institute's mission and vision. We have found this happens as by-product of how we conduct the director search.

One difference between an ISR director and a department chair stems from the interdisciplinary nature of ISR. The ISR director needs to develop mechanisms that encourage interdisciplinary research, and hold such research as a standard for faculty. One of these mechanisms has been to require interdisciplinary research as part of the criteria for promotion—something that is not typically required in a traditional department.

ISR's initiatives in robotics, green communications, and microsystems are three good examples of the interdisciplinary fields developed by ISR's current director, Reza Ghodssi. These initiatives are drawing together not only ISR faculty from different disciplines, but also non-ISR faculty from across the university. In addition, Ghodssi has developed a colloquia series that is held monthly throughout the academic year. It features ISR faculty from various disciplines speaking in-depth about their research, and is designed to help ISR faculty and students learn about and be inspired by disciplines different from their own.

Because the institute functions best with distributed management and leadership, there is a recognized need to train younger faculty so they can effectively take on leadership roles as ISR continues to grow. Faculty need support and training to be able to lead major projects. A current example of this is the mentoring S.K. Gupta has received from Reza Ghodssi and other faculty since he became director of the Maryland Robotics Center in 2010.

b. Did the disciplinary composition of the ERC change over time? If so, how and for what purpose?

In 1985 the main research theme and vision of the Systems Research Center (ISR) was the computer-aided design of complex automatic control and communication systems. This was to be accomplished through fundamental research that synergistically combined advances in three types of technology (VLSI, CAD, and AI) with sophisticated control and communication methodologies. The research plan included fundamental research in modeling, optimization, computational and numerical methods and techniques for control systems, communication systems, and computer engineering. This was accomplished in five research areas: intelligent CAD of stochastic systems, intelligent servomechanisms, chemical process control, advanced automation and information processing in manufacturing systems, and telecommunication systems.

ISR became known for its research integrating intelligent control, signal processing and communication, computation, and systems integration methodology. Over the years, the composition of ISR research expanded to include applications in biology, psychology, and zoology that were not present at the start.

In the late 1990s, during the term of Director Gary Rubloff, ISR research evolved into the "federation of centers" model. NSF's ERC investment in fundamental systems research themes had led to a federation of major programs and activities which reflected the initial systems engineering core. The research approaches at the time were sensor-actuator networks, media information systems, global communication systems, societal infrastructure systems and next-generation product realization systems. All were built on ISR's systems strengths of control, communications, and computing; optimization and tradeoff analysis; modeling, simulation, databases; operations research; AI planning; and human factors.

ISR has moved into new areas of research based on the interests of faculty, whether or not there is funding available. The institute does not enter areas just because there is funding in that area. Instead we try to build on strengths that are in the faculty, and hire faculty in areas that are starting to come to the fore. The funding will come if our people do a good job. We consider this a "bottom up" approach rather than a "top down" approach.

Some of ISR's most active research areas today began in this manner. For example, ISR currently has a strong emphasis on neuroscience research that crosses the disciplines of electrical and computer engineering, psychology, mechanical engineering, biology, aerospace engineering, bioengineering, and computer science. This research encompasses the domains of neural signal processing in the auditory cortex; brain development, plasticity, and function; neuromechanical systems, locomotion, and spinal regeneration; speech recognition, production and enhancement; neuromorphic-based control of robotics systems; neuromorphic VLSI design; computational neuroscience; biological cell-based sensor systems; and signal processing in biological systems. ISR's collegial, interdisciplinary atmosphere among existing faculty with an interest in the broad topic of neuroscience led to funding, which led to additional faculty being recruited in this area for joint appointments and affiliations, which led to further expanded research and the creation of

a number of postdoctoral positions. ISR's focus in this area helps to attract both undergraduate and graduate students who have an interest in biology, in neuroscience in particular, and in career paths that are at the interface of these fields and electrical and computer engineering. Faculty members of this group are actively involved in the campus graduate program in Neuroscience and Cognitive Science (NACS).

ISR's interest in micro and nanotechnology began in this way as well. ISR Director Gary Rubloff developed an interest in this area during his term and brought current Director Reza Ghodssi—a MEMS specialist—to the university as a junior faculty member. After a number of years of increasing activity, several units within the university were interested in forming a center for micro and nanotechnology, which became the Maryland NanoCenter.

Today ISR considers its main research areas to be communication systems and networks; control systems and methodologies; systems engineering methodologies; neuroscience and biology-based technologies; micro and nano devices and systems; design, operations, and supply chain management; and computing, speech, artificial intelligence and data mining; plus the three new initiatives of microsystems, robotics, and green communications.

c. What mechanism does ISR use in selecting participating faculty? How does ISR choose and evaluate its faculty? What methods have had a particular impact on its success? What is the relationship with their home departments regarding time, promotion and tenure, etc.?

ISR joint appointments are three-year rotating appointments. A faculty member applies and is evaluated by an ISR APT committee. This committee is partly elected and partly appointed. It evaluates all candidates and makes recommendations to the ISR director, who makes the final decisions. Obviously, ISR looks for quality and excellence, but the appointment is also based on interdisciplinary work.

It is difficult for an isolated researcher to fit into ISR, with its emphasis on collegiality and interdisciplinary research. ISR lets prospective joint appointment and affiliated faculty know that they are expected to interact with other faculty, and one of the criteria during the review is that the committee sees evidence that this is already occurring.

Ben Shapiro is a good example of a faculty member who fits well with ISR. Shapiro came to the university as an aerospace engineer, yet he already had experience in control theory. ISR had a need for a faculty member in aerospace engineering. Shapiro's work in microfluidics was in line with where ISR was headed. Along with Pamela Abshire and Elisabeth Smela, Shapiro became interested in biological cell-based sensors and began to specialize in the

control of fluidics in these chips. Because of the evolution of his research interests through his experience in ISR, recently Shapiro switched from aerospace engineering to bioengineering. For some of our junior faculty, being in ISR is similar to an internship, in that it exposes them to new fields and allows their research to change and grow organically.

ISR has official input into both the promotion and salary process for its jointly appointed faculty.

2. Impact on the University of Maryland

a. How has ISR influenced the University of Maryland campus in general?

Adding ISR to the University of Maryland brought prestige to the university and the A. James Clark School of Engineering. Because NSF chose the Clark School to be the home of one of the first six ERCs, the college became recognized as a place of quality and excellence. Today it is hard to imagine what a huge accomplishment this was at the time. It meant the university and the college were viewed as first class—Maryland was one of only six universities in the country to be so honored. It put ISR in a new league; it was like winning the World Series.

The university and its colleges benefitted from the association with ISR in several key disciplines—systems science and engineering, certainly, but also in electrical and computer engineering, mechanical engineering, and chemical engineering within the Clark School. The Robert H. Smith School of Business and the College of Computer, Mathematical and Physical Science also benefitted from the joint appointments.

ISR, with its deliberate interdisciplinary focus, was the catalyst that jump-started interdisciplinary research within the Clark School and in other colleges where ISR faculty held joint appointments. Today this intellectual cross-fertilization is much more common within departments, at the university, and indeed throughout academia. But in 1985 such concepts were quite new. There is no question that interdisciplinary research at the University of Maryland grew much faster because of ISR's presence. ISR sought the growth of interdisciplinary community, even if it meant bringing a faculty member to an institute *other than ISR* within the university.

b. How has ISR contributed to the University of Maryland in generating and promoting institutions/programs of science?

Throughout its history, ISR has been an innovative leader within the university in developing both short- and long-term research programs and centers. Perhaps our earliest effort in this area was the development of the NASA Center for the Commercial Development of Space, or **CCDS**, a leading-edge center for telecommunications. Led by ISR

Founding Director John Baras, in the mid-1990s this center became known as CSHCN, the Center for Satellite and Hybrid Communications Networks, and then, early in this decade as HyNet, the Hybrid Networks Center. The pioneering DirecTV work with Hughes Network Systems took place within this center.

The Center for Advanced Life Cycle Engineering Electronics Products and Systems Center (CALCE) was established in 1986 within ISR. Due to its success, within a few years, CALCE became an independently funded center. Today CALCE is the largest electronic products and systems research center focused on electronics reliability and an internationally recognized leader in reliability assessment of electronics based on physics of failure analysis. CALCE has grown into a consortium with almost $45 million in combined research support in the past 15 years. The center employs more than 100 faculty, research staff and graduate students from almost every engineering discipline. (*www.calce.umd.edu*)

Another example of a long-running ISR-related center is **NEXTOR**, the Federal Aviation Administration Center of Excellence in Aviation Operations Research (*www.nextor. org*). This center's objectives are to advance new ideas and paradigms for aviation operations, to educate and train aviation professionals, and promote knowledge transfer among industry, government, and academic leaders. The Maryland part of the initiative is led by Michael Ball. ISR provides office space for NEXTOR and has hosted several national meetings that brought together airline industry executives and federal regulators. In addition to the University of Maryland, the consortium includes George Mason University, the Massachusetts Institute of Technology, the University of California at Berkeley, and Virginia Polytechnic Institute and State University.

The Maryland NanoCenter (*www.nanocenter.umd.edu*), founded by former ISR Director Gary Rubloff, also is a successful center based on the ISR model. Rubloff's relationship with current ISR Director Reza Ghodssi, an expert in micro electromechanical systems (MEMS); and William Bentley, chair of the Fischell Department of Bioengineering; were instrumental in developing this center. The Maryland NanoCenter enhances the coherence and effectiveness of the University of Maryland nano community by coordinating shared state-of-art experimental facilities; developing best practices for administrative infrastructure supports; providing coherent, broad visibility at state, national, and international levels; encouraging and facilitating nano program growth and fund-raising; guiding the evolution of coordinated educational programs for the nano workforce of the future; and promoting the development and transfer of nanotechnology and related intellectual property to the marketplace. ISR was the reason much of this became possible.

The Maryland Robotics Center (*robotics.umd.edu*) is a current example of a new research hub for the university that has come from ISR's ERC thinking, strategy and infrastructure. Along the way, other centers that found a home within ISR have included the Center for Auditory and Acoustic Research, led by Shihab Shamma; the Center for Dynamics and Control of Smart Structures, led by P. S. Krishnaprasad and John Baillieul (Boston University); the Center for Engineered Learning Systems, led by Gary Rubloff; and the Center for Communicating Networked Control Systems, led by P. S. Krishnaprasad, John Baillieul, Roger Brockett, and P. R. Kumar (University of Illinois).

c. How has ISR contributed to the University in attracting resources such as talent, research grants, etc.?

By the early 1990s, faculty were being drawn to the University of Maryland specifically to work in ISR. In addition, current faculty within the university eagerly seek joint appointments or affiliations with the institute on a regular basis.

Of ISR's five directors, two were already University of Maryland faculty, but three came to the university specifically to work with ISR. Steve Marcus originally was recruited from the University of Texas to be ISR Director in 1991, while Gary Rubloff came from North Carolina State University to become director in 1996. Reza Ghodssi, ISR's current director, came to the university at the start of his academic career as an ISR joint appointment; being able to be a part of ISR weighed heavily in his decision.

Beyond these directors, many other faculty chose the University of Maryland based on the ability to be associated with ISR. For example, S.K. Gupta, director of ISR's new Maryland Robotics Center, completed his Ph.D. work at Maryland with Dana Nau, who specializes in artificial intelligence planning. In large part because of his exposure to ISR as a graduate student, and the offer of a joint appointment with ISR afterwards, Gupta chose the University of Maryland for his academic career.

Another faculty example is Pamela Abshire, who directs the Integrated Biomorphic Information Systems Laboratory and conducts interdisciplinary research with ISR colleagues in Mechanical Engineering and Bioengineering that enables the hybrid integration of biological cells into microelectronic systems, making possible the development of cell-based sensors. Abshire was attracted to the University of Maryland at the start of her academic career by the offer of a joint appointment with ISR that would allow her to conduct this type of collaborative research.

Many faculty who are in Mechanical Engineering and Electrical and Computer Engineering today were initially attracted to those departments in part because of ISR joint appointments.

The collegial atmosphere created by ISR among faculty from many different disciplines lends itself to collaborating on proposals for interdisciplinary research, with a high level of innovation.

d. Provide some examples of how the participating faculty and students benefit from ISR's structure and mode of operation.

ISR gives faculty and students a place to pursue interesting interdisciplinary research projects in combinations beyond what one would experience within a department. Groups of faculty and students come together for these projects and everyone learns from each other. Students benefit from attending research meetings with faculty from a number of areas and disciplines. Following are examples of the kinds of projects that are undertaken with great frequency at ISR, and their benefits to those involved.

Next-Generation Model Checking and Abstract Interpretation with a Focus on Embedded Control and Systems Biology is a current, five-year, $10 million project that is part of NSF's "Expeditions in Computing" initiative (*cmacs.cs.cmu.edu*). The program is led by Carnegie Mellon University with collaboration from ISR and the School of Public Health at the University of Maryland, the City University of New York, New York University, SUNY Stony Brook, Cornell University, and NASA's Jet Propulsion Laboratory.

The Maryland portion of the multidisciplinary project brings together a team of faculty who previously had not worked together. Rance Cleaveland (joint appointment with Computer Science), an embedded software researcher, is the principal investigator; while co-PIs are former ISR Director Steve Marcus, who specializes in control theory; and Tongtong Wu, a biostatistics expert in the School of Public Health. Team members would not have known about each other's research interests and specialties or pursued this opportunity had Cleaveland and Marcus not met through their association with ISR.

The team is developing revolutionary techniques for automatically analyzing and predicting the behavior of biological and control systems. The techniques will help scientists and engineers accelerate the pace of their discoveries by automating tasks that currently must be manually performed.

The Integrating Product Dynamics and Process Models (IPDPM) into Operational Methods project is an example from shortly after ISR's graduation (circa 1998–2000). This project developed new operational methods that enable efficient manufacturing operations during the wafer fabrication life cycle in semiconductor manufacturing. The project was jointly sponsored by NSF and the Semiconductor Research Corporation and was part of the NSF/SRC Virtual Center on Operational Methods in Semiconductor Manufacturing.

This project brought together four ISR joint appointment faculty from diverse disciplines: Steve Marcus (Electrical and Computer Engineering), then-ISR Director Gary Rubloff (Materials Science and Engineering), Michael Fu (Decision and Information Technologies in the Robert H. Smith School of Business), and Jeffrey Herrmann (Mechanical Engineering).

The project proceeded along two research lines: integrating product and market dynamics into operational decision making, and incorporating process and cluster tool models into simulation models of manufacturing operations. The first included finite-horizon, Markov decision process models that incorporated transient fabrication characteristics and supported decisions throughout the wafer fabrication life cycle. Such models handled the product market's complex dynamics and supported the technologies that enabled efficient manufacturing for the right products at the right time.

The second research line integrated manufacturing operations and process models so that decisionmakers could predict how process improvements and changes affected the wafer fabrication's production objectives (throughput, cycle time, and cost, for instance). The modeling and sensitivity analysis techniques incorporated response surface models, which described manufacturing processes; and simulation and scheduling techniques, which evaluated the manufacturing system.

Just as concurrent engineering yielded better product designs by teaming design and manufacturing engineers, the IPDPM project improved wafer fabrication operations by teaming engineers and managers throughout the wafer fabrication: those who design and control manufacturing processes, those who manage manufacturing operations, those who design and build wafer fabs, and those who design and introduce new products. The results yielded specific insights into the structure of optimal operational policies and the sensitivity of operational decisions to underlying process parameters. Operational and factory integration personnel were able to use these insights to suggest and justify changes to operational policies and manufacturing processes.

Had these faculty not known about each other and their research interests through their mutual association within ISR's collaborative environment, this research project might not have been undertaken.

Career-shaping experiences for students. Xiaobo Tan, now a tenured professor of Electrical and Computer Engineering at Michigan State University, provides a good example of how the collaborative atmosphere of ISR can shape Ph.D. students. Tan was an ISR Systems Fellow from 1998 to 2002 and earned his Ph.D. in Electrical and Computer Engineering in 2002, advised by two ISR joint appointment faculty, John Baras and P. S. Krishnaprasad. Tan's Ph.D. thesis focused on the modeling and control of hysteresis in smart materials, and was theoretical in nature.

After graduation, Tan conducted postdoctoral research with Baras on networked control systems and also worked with another ISR joint appointment faculty member, Reza Ghodssi, on the characterization and modeling of frictional behaviors of linear microball bearings. His research interests now incorporated experimental as well as theoretical engineering.

Shortly after taking a tenure-track faculty position at MSU, Tan won an NSF CAREER Award for his research, "Dexterous Biomimetic Micromanipulation Using Artificial Muscles: Modeling, Sensing and Control," and became director of the Smart Microsystems Laboratory. He went on to receive an Office of Naval Research grant to develop highly maneuverable "biomimetic" robotic fish, which has since become the focus of his research. He received an NSF grant in 2009 for "AquaSWARM: Small Wireless Autonomous Robots for Monitoring of Aquatic Environments." This interdisciplinary grant is integrating his work with that of MSU Zoology Professor Elena Lichtman. Tan also leads an NSF "Research Experiences for Teachers" program at MSU and in 2010 received MSU's Scholar-Teacher Award.

The collaborative, interdisciplinary environment of ISR was a key factor in exposing Tan to both theoretical and experimental pursuits in a variety of disciplines; these traits continue in his research at MSU today.

e. What ISR courses, books and ways to educate and train have made an impact on the University?

Courses. During the past 25 years, ISR faculty have played a pivotal role in the development of interdisciplinary education programs. The MSSE and REU programs are perhaps the best examples. Within the larger community, support for the ENPM systems programs, QUEST and Engineers Without Borders are the best examples.

During the past decade, and with funding from an NSF CRCD grant and industry, we have completely re-designed and re-implemented the ENSE 621-622-623 core course sequence. We have field tested the new material with a number of large U.S. companies (e.g., GE Transportation Systems, GE Industrial Systems, Lockheed Martin, IN-COSE Tutorials). Feedback from these exercises is one of the best ways of making sure that we are relevant to our future customers and that our focus remains on the solution of problems important to the professional systems engineering community. This improves our education program and, in turn, the reputation of the university both within the state and nationally.

Ways to educate and train. Ph.D. students advised by ISR faculty frequently become part of interdisciplinary research teams and attend research meetings led by faculty outside their home disciplines. Moreover, Ph.D. students often are formally co-supervised by faculty from different disciplines. This is one of the unique aspects of an ISR education, and in terms of training and education, one of ISR's biggest contributions.

For example, Steve Marcus and Michael Fu in recent years often have teamed on research grants and co-advised students. In 2009, the paper "A Numerical Method for Financial Decision Problems under Stochastic Volatility," by Marcus, Fu, and their students Enlu Zhou and Kun Lin, won the Best Theoretical Paper Award at the 2009 Winter Simulation Conference (WSC). WSC is the premier international forum for disseminating recent advances in the field of system simulation. Zhou earned an Electrical and Computer Engineering Ph.D. in 2009, co-advised by Marcus and Fu. She is now an assistant professor at the University of Illinois Urbana-Champaign. Kun Lin is a current ECE/ISR Ph.D. student, also co-advised by Marcus and Fu.

ISR students can take advantage of seminars by visiting scholars and distinguished lecturers from various disciplines several times a week. In addition, every month during the academic year ISR sponsors a colloquium for the ISR community—especially its graduate students—that features an ISR faculty member speaking about his or her research. These colloquia introduce students to fields they may not otherwise have considered, and can lead to new fields of inquiry.

Books. ISR faculty, often in conjunction with their students and alumni, have published more than 60 books. We note a few of these publications below; a select list of publications is on ISR's website at *www.isr.umd.edu/faculty/books_software.htm*.

The Control Handbook by William S. Levine was first published by CRC in 1996; a greatly expanded second edition is forthcoming in December 2010. Widely recognized as the defining book for the field of control systems, the book's enormous and unique scope, coupled with its excellent organization by a first-class advisory panel quickly made it a standard reference. The award-winning, bestselling handbook reflects not only the field's advances but also its expansion.

Building Scientific Apparatus, by Christopher Davis (ISR), John H. Moore, Michael A. Coplan and Sandra C. Greer, was first published by Cambridge University Press in 1989. In 2009 it entered its fourth edition. Unrivaled in its coverage and unique in its hands-on approach, this practical guide to the design and construction of laboratory instruments is essential reading for every scientist and student of engineering, and physical, chemical, and biological sciences.

Guangming Zhang (ISR joint appointment with Mechanical Engineering) has written textbooks and received many teaching awards over his long career. His textbook, *Engineering Design and Pro/ENGINEER Wildfire*, published by College House Enterprises, is currently in its fourth edition. With other University of Maryland faculty, he is an author of *Introduction to Engineering Design, Book 9: Engineering Skills and Hovercraft Missions,* Third Edition, published by College House Enterprises in 2008. Zhang won the A. James Clark School of Engineering's Poole and Kent Outstanding Teaching Award for Senior Faculty in 2004, and was one of the Clark School's first six Keystone Professors in 2006. The Keystone program honors faculty with exemplary teaching skills and commitment to fundamental engineering courses. That same year, students in the Clark School's Professional Master of Engineering Program (ENPM) selected Zhang as the first recipient of the Outstanding Teaching Award.

Ben Shneiderman, "the father of information visualization," is the author of many textbooks. His *Designing the*

User Interface: Strategies for Effective Human-Computer Interaction, published by Addison Wesley, is now in its fifth edition. The book, by Shneiderman and his colleagues Catherine Plaisant, Maxine Cohen, and Steven Jacobs, is considered the standard textbook in the field. Other books by Shneiderman include the new *Analyzing Social Media Networks with NodeXL: Insights from a Connected World,* published by Morgan Kauffmann, 2010; and *Leonardo's Laptop: Human Needs and the New Computing Technologies*, published by The MIT Press in 2003.

Automated Planning, by Dana Nau (ISR), Malik Ghallab and Paolo Traverso, was published by Morgan Kauffmann in 2004. It is a comprehensive, current synthesis that has become the standard textbook in the artificial intelligence planning field.

Introduction to Cryptography with Coding Theory, by ISR alumnus Wade Trappe and Lawrence Washington of the Mathematics Department, published by Prentice Hall, is in its second edition. The text was written when Trappe was an ISR-affiliated Ph.D. student and is aimed at engineers who are interested in learning more about cryptography. It mixes applied and theoretical aspects for a solid introduction to cryptography and security, including the latest significant advancements in the field.

MEMS Materials and Processes Handbook, edited by ISR Director Reza Ghodssi and Pinyen Lin will be published by Springer in January 2011. This comprehensive 1,000-page collection of case studies for students, researchers and engineers reveals laboratory secrets and illustrates how different microfabrication processes are accomplished. It also guides the reader through the selection of appropriate materials for the required task at hand. Thirty-five international authors are represented.

A select list of ISR books and software can be found on ISR's web site at *www.isr.umd.edu/faculty/books_software.htm*.

H. ISR Sustainability Post– Graduation from NSF ERC Program Support

1. What model did ISR use to configure itself after the NSF ERC Program support ceased and how has that evolved?

Early on, from 1988-1991, ISR defined, developed and tested organizational, financial, industry-university collaboration, and academic structures. For example, ISR maintained about 40 three-year renewable joint faculty appointments. ISR faculty, postdoctoral researchers, students, offices and many labs have been housed in 80,000 to 90,000 square feet of contiguous space since 1988. ISR has had a core of six constituent-group laboratories for many years, and a strong international Strategic Advisory Council, as well as several industry-specific advisory teams. During the ERC period, ISR built an excellent administrative and technical support staff. This infrastructure allowed ISR to create many interdisciplinary centers within itself, some long lasting and some ephemeral, which were a factor in maintaining the institute's forward momentum over the years.

Since graduation, ISR has essentially retained the foundations of the ERC model, with minor tuning.

The most important factor is that ISR is a permanent institute—permanently funded by the state of Maryland—on the same level as departments within the A. James Clark School of Engineering. ISR leaders proactively secured this status long before the ERC funding ceased. ISR's leaders knew that life would be more difficult if the institute did not have the large central directed funding that NSF had given it as an ERC.

Early in ISR's existence, Founding Director John Baras undertook two efforts key to long-term viability. First, he established a leading-edge center for telecommunications (initially known as the NASA Center for the Commercial Development of Space, or CCDS) within ISR, which brought together the spectrum of ISR skills in systems research in a coherent way. CCDS allowed ISR's expertise in systems research to be focused on an emerging growth industry and application. This applications focus added an important intellectual dimension, namely the opportunity to reveal systems research needs from the perspective of an application.

Second, with special support from university higher administration, Baras leveraged ISR's success in establishing the CCDS to obtain institute status and permanent funding from the state of Maryland. This achievement solidified ISR's role in the college and university, assured long-term financial and administrative support for ISR pursuits, provided a stable basis for creating new centers and major programs, and won the confidence of outstanding ERC faculty. Since these two developments occurred midway in the funding lifetime of the ERC, they emphasize how critical strategic planning and management are throughout the life cycle of an ERC. We will elaborate on this process in the next section.

From the beginning, ISR has emphasized the long term and taken steps to become self-supporting. We have retained faculty with interdisciplinary interests who have performed well. We have struck a balance between short-term and long-term research. We have attracted the very best graduate and undergraduate students and given them a unique and nurturing environment. We have emphasized engineering research for undergraduates. We have created strong interdisciplinary team labs and supplied them with technical support personnel.

2. How did ISR establish a financial basis for its continued function and growth after ISR graduated from NSF ERC Program funding?

ISR received two rounds of NSF funding in the period 1985–1998. The most critical step towards a self-sustainable

ERC was the case made in 1987–1988—only two years into our initial funding—to the State of Maryland. ISR argued, with strong support from university and industry leaders, to receive permanent funding and become a interdisciplinary University of Maryland institute. The key argument made was the positive impact of SRC/ISR programs on the state's economic development.

When John Baras sought and received the permanent funding for ISR from the Maryland state government, the University of Maryland already had a structure that included institutes with joint appointments. His funding request occurred in the context of two previous university institutes having recently and successfully done the same thing: the Institute for Physical Science and Technology (IPST), and the University of Maryland Institute for Advanced Computer Studies (UMIACS). Baras followed their lead, which made it easier for ISR to get funding. The University of Maryland also had a very supportive provost at the time who provided critical assistance: William "Brit" Kirwan, the current chancellor of the University System of Maryland.

The support of the provost and top management is essential. When making decisions about funding new ERCs, NSF should look at how forward looking the university is in other areas. Is the university looking to the future and making tough decisions? Do they have the kind of nerve to think outside the box in a way an ERC would need to be sustainable in the long term?

NSF should work with university management, especially the provost, throughout the life of an ERC to make sure the ERC is a success. One of ISR's strategies was to meet with the president of the university every year. The ERC needs to have direct access to the provost and president. NSF's presence in these meetings helps the ERC increase its visibility to the president and provost.

ISR also learned how important it was to secure money for permanent funding while everyone was still excited about the ERC. Ten years into ISR's existence the mood had shifted. This is an important lesson. When NSF funding is ending, it is not the time to ask for permanent funding for the ERC. The time to ask is much earlier than that, which is what founding Director John Baras did.

In 1989 the State of Maryland appropriated permanent state funding to ISR at $3 million per year, implemented progressively. In 1992, the ERC became a permanent interdisciplinary institute of University of Maryland and was renamed the Institute for Systems Research.

3. What distinctive ERC features fell by the wayside after NSF support ended—interdisciplinary teams, precollege programs, undergraduate outreach, testbeds?

The most *immediate* loss was that of our K–12 programming; the longest-running and most significant being the Young Scholars program. This program has not been revived since

NSF support ended. The most *significant* losses were to our ISR Fellows and ISR Postdoctoral Fellows programs. In the case of ISR Fellows, we had given fellowships from our ERC funding to attract good graduate students. Our ISR Postdoctoral Fellows program was a competition funded through ERC and other sources. As noted earlier, ISR did continue to have Research Experiences for Undergraduates (REU) programs for most years through 2008.

The number of ISR faculty, staff researchers, graduate and undergraduate students increased initially but leveled off as the economy deteriorated. The number of postdoctoral researchers and state-funded research staff positions decreased. Administrative staff loss has been significant within ISR's infrastructure. During the NSF-funded years ISR was able to retain administrative staff that helped ISR accomplish its mandate, as well as the structure and support NSF wanted for its ERCs. Once ERC funding ceased, the number of administrative staff positions steadily decreased as a result of the economy and problems with the state budget. There are fewer staff in ISR today than at any point in its history (less than one-third of ISR administrative staff positions established during the NSF years remain). This has limited what ISR is able to accomplish, and put significant stress on the remaining staff.

4. Does ISR consider itself a successful sustained ERC or something else?

ISR considers itself a successful, sustained ERC.

5. Did ISR continue as a interdisciplinary center; if so how or if not why not?

ISR has continued as an interdisciplinary center.

6. How much did the ERC structure and influence contribute to ISR's continued success?

Even though ISR graduated from the ERC program 12 years ago, the ERC structure continues to be the basis of how ISR operates and a major contributor to its success. The ERC structure created a culture that faculty, staff and students bought into over the years, and are still embracing today.

Visitors to ISR are always impressed with how much is going on here. We attribute this in part to the discipline the ERC structure imposed on ISR from the start. Both the annual reviews and the three-year reviews forced ISR into a rhythm and method of accomplishment which has not diminished over the years. The ERC administrative staff mandate enabled a high level of service to faculty, students, and industry and government representatives. This is still the case today.

An engineered systems focus continues to drive ISR's research. ISR still adheres to the general organizing principle of integrating research, education and industrial interaction. Interdisciplinary research collaborations continue and have

been augmented and testbeds continue to be employed to pursue proof-of-concept of enabling and systems technology. Graduate and undergraduate students participate in interdisciplinary research teams and are involved in systems level activities. ISR's research continues to enhance curriculum and degree programs throughout the college and university. A strong level of industrial/practitioner involvement guides new directions, and financially supports ISR.

7. What general lessons can be drawn from ISR's experience post-NSF on how to succeed as a graduated ERC?

When NSF funding ended in 1998, two major challenges surfaced. The first was sustaining a "systems synthesis focus" in most projects. The second was maintaining and expanding the set of industry sponsors and collaborations. Both were met with varying success by creating several smaller centers and by winning large interdisciplinary projects like MURIs and ARL Collaborative Technology Alliances. As previously mentioned, there was a shift in industry support towards projects with a narrower focus and a short-range research outlook.

Support from the state of Maryland and status as a permanent institute maintained ISR's high international visibility.

Post ERC-graduation, both University of Maryland and external faculty, students and postdoctoral researchers continued to intensively seek ISR affiliation.

After NSF funding ceased, ISR no longer had large, central, self-directed funds for long-range systems synthesis research; our smaller centers and industry funding helped, but they also added constraints. In addition, two elite centrally funded ISR programs ended: the ISR Fellows program, which helped recruit some truly outstanding graduate students; and the ISR Postdoctoral Fellows program, which brought many young scientists to ISR for mentoring and contribution to our programs.

We believe NSF's background assumptions about self-sufficiency were not altogether realistic. Securing sufficient funding to first achieve and then maintain self-sufficiency is a very difficult task. It is also one that in many ways does not end with permanent institute status. It has been difficult to maintain our share of state funding within the college and the greater university. We often disproportionately bear a greater burden of cutbacks than departments within the college. The shrinking number of ISR staff over the past decade is one indicator of this continual struggle. In the current economic climate, we are challenged to make our self-support model even more entrepreneurial than it has been in the past to maintain self sufficiency.

The best aspect of life as an NSF ERC was teaming across disciplines to pursue opportunities and visionary projects that individual investigators could not have done alone.

In our post-ERC life we continue to experience vigor among the faculty to pursue exciting interdisciplinary projects. We have not wavered from the principle of quality,

both in our research and in our people. On the other hand, we feel it is a never-ending battle to internally remind the university about ISR and its worth. ISR has found through the years that it needs to heavily promote itself, its mission and its value to the university, not only to counteract assumptions and misconceptions, but simply to remain visible. One example of this is ISR often being "forgotten," by departments, the college, the university communications office, the vice president for research's office, and other university-wide entities when joint appointment (let alone affiliated) faculty serve on committees, win awards, make the news, are featured in public relations and marketing campaigns, etc. We sometimes have this problem with our own joint faculty as well. A frequent example is when faculty forget to mention ties to ISR when giving presentations within and outside the university.

Industrial participation in ISR research remains important. On an absolute scale, the number of companies we work with has remained about level and funding has remained strong. The composition of our industry collaborators has changed in sync with the evolution of our research program. We also have added additional mechanisms for collaborating with industry.

Faculty experience different expectations and responsibilities within ISR and work differently than they would if their appointment were solely in a department. For example, interaction with colleagues in other disciplines and other departments and institutes is expected within ISR. In a department, you can hunker down as a scholar within a narrow discipline and spend your academic career there—that is a perfectly acceptable way of succeeding as a departmental faculty member. At ISR, interdisciplinary collaboration is expected and part of the criteria in the review. ISR joint appointment faculty are reviewed every three years, and some appointments, even by well-respected researchers, have not continued when these criteria have not been met.

ISR students' exposure to interdisciplinary research is a continuing advantage as well. Students see their ISR faculty advisors working with colleagues across disciplines, they sit in on research meetings with them, and they work with them on their interdisciplinary projects. This broadens the students' exposure to fields outside their own and helps them see possibilities for collaborative work. ISR has always been the kind of place where this can happen for students.

We have learned that universities are driven by **impact,** and that long term impact is far better than short term impact. Qualitative, transformational impact is far better than numerical accounts. The best metrics of impact for engineering are our graduates and what they do; industrial practice and creation of new sectors; patents and inventions that lead to innovations that change an industry sector or the way we work and live; seminal publications that change the knowledge basis or the way we think; new courses, books, and ways to educate and train; and the international stature of faculty and programs.

Appendix: Selected ISR alumni and their employers

Communication Systems and Networks

Deepak Ayyagari, Sharp Laboratories

Partha Bhattacharya, Cisco Systems

Jie Chen, University of Alberta

Ching-Te Chiu, Macronix (Taiwan)

M. Scott Corson, Qualcomm

Hesham El-Gamal, Ohio State University

Aaron Falk, BBN Technologies

Azadeh Faridi, Pompeu Fabra University, Spain

Reza Ghanadan, BAE Systems, Inc.

Junfeng Gu, Cisco Systems

John Gubner, University of Wisconsin

Zhu Han, Boise State University

Hamid Jafarkhani, University of California, Irvine

Matthew James, Australian National University

Yimin Jiang, Availink

Mehdi Kalantari, ECE Dept., UMD

Koushik Kar, Rensselaer Polytechnic University

Damianos Karakos, Johns Hopkins University

Onur Kaya, Isik University, Turkey

Sanjeev Khudanpur, Johns Hopkins University

Ut-Va Koc, Alcatel-Lucent Bell Labs

Andres Kwasinski, Rochester Institute of Technology

Rajeev Laroia, QUALCOMM

Anthony LaVigna, Multimed Technical Services

Mingyan Liu, University of Michigan

Eytan Modiano, Massachusetts Institute of Technology

Anna Pantelidou, University of Oulu, Finland

Radha Poovendran, University of Washington

Ramesh Rao, UC San Diego

Farrokh Rashid-Farrokhi (employer?)

Ramin Rezaiifar, QUALCOMM

Zoltan Safar, Samsung

Balaji Sampath, Association for India's Development

Saswati Sarkar, University of Pennsylvania

Reza Shahidi, QUALCOMM

Nikos Sidiropoulos, Technical University of Crete

Yan Lindsay Sun, University of Rhode Island

Leandros Tassiulas, University of Thessala, Greece

Carol Teolis, TRX Systems, Inc.

Wade Trappe, Rutgers University

Sumesh Udayakumaran, Intel

Subir Varmma, Aperto Networks

Ioannis Viniotis, North Carolina State University

David Walnut (employer?)

Z. Jane Wang, University of British Columbia

Philip Wiser, Sezmi Corporation

Paul Yu, Army Research Laboratory

Haitao (Heather) Zheng, US-Santa Barbara

H. Vicky Zhao, University of Alberta

Control Systems and Methodologies

Sean Andersson, Boston University

Naveen Bhat, Ixia

Xin (Cindy) Chen, Leadership Management International

Yung-Shan Chou, Tamkang University

Stefano Coraluppi, NATO Undersea Research Center

Michael Fan, AEM Technology

Pedram Fard, Global Products, Inc.

Ram Venkataraman Iyer, Texas Tech University

Sameer Joshi, Pathway Technologies

Eric Justh, Naval Research Laboratory

George Kantor, Carnegie Mellon University

Craig Lawrence, BAE Systems

Naomi Leonard, Princeton University

Li Lee, National Sun-Yat Sen University

Vikram Manikonda, Intelligent Automation, Inc.

Andrew Newman, Johns Hopkins University Applied Physics Laboratory

Yagyensh (Buno) Pati, Sezmi, Inc.

Vahid Ramezani, Avyna

Priya Ranjan, Indian Institute of Technology Kanpur

Vineet Sahasrabudhe, Sikorsky Aircraft

Lahcen Saydy, Ecole Polytechnique de Montreal

Narasingarao Sreenath, Case Western Reserve University

Richard Stamper, Rose-Hulman Institute of Technology

Herbert Struemper, Pharsight

Xiaobo Tan, Michigan State University

Dimitrios Tsakiris, Institute of Computer Science, Foundation for Research and Technology - Hellas (FORTH)

Nam-Kiu Tsing, University of Hong Kong

Gregory Walsh, Leica Geosystems HDS

Lisheng Wang, National Taiwan University

Rui Yang, InterDigital Corporation

Luke Winternitz, NASA Goddard Space Flight Center

Fumin Zhang, Georgia Institute of Technology

Systems Engineering Methodologies

Anubhav Arora, Alcatel-Lucent

Sundar Balasubramanian, British Telecom

William Bennett, BAE Systems

Narender Bhogadi, TransUnion LLC

Antonio Cardone, NIST

Chien Yu Chen, George Mason University

Mandar Chincholkar, Intel Corp.

Duk-Hi Chun, Korean Air Operations Control Central

Stefano Coraluppi, NATO Undersea Research Center

M. Scott Corson, Qualcomm Flarion Technologies

Anindya Datta (unknown)

Robert Day, University of Connecticut

Majid Raissi Dehkordi, OPNET Technologies, Inc.

David Delalio, Meso Scale Diagnostics, LLC

Abhijit Deshmukh, Actify, Inc.

Mustafa Eroz, Hughes Network Systems

Sean Gahagan, Northrop Grumman

Ken Gerber, i2 Technologies

Reza Ghanadan, BAE Systems, Inc.

Ingar Grev, Raytheon

Ying He, NIH

Sara Hewitt, TRW

Ali Hirsa, Caspian Capital Management

Robert Hoffman, Metron Aviation

John Hopkins, Northrop Grumman Ship Systems

Pedram Hovareshti, University of Maryland

William Howell, BAE Systems

Jiaqiao Hu, SUNY Stonybrook

Jun Huang, UGS PLM Solutions

Tasha Inniss, Spelman College

Sivaramakrishana Iyer, Honeywell

Matthew James, Australian National University

Tachyung Kim, Korea Transport Institute

Scott Laprise, BAE Systems

Jason Li, IAI

Feng Lee Lin, National Sun Yat Sen University

Mingyan Liu, University of Michigan

Adrian Marsh, U.S. Army

Vidit Mathur, Verizon

Vimal Mayank, Wachovia Corp.

Julie McNeil, General Dynamics

Archan Misra, IBM TJ Watson Research Center

Avijit Mukherjee, NASA Ames Research Center

Dung Hanh Nguyen, Lockheed Martin

Vera Osidach, Centers for Disease Control

Nital Patel, Intel Corp.

Radha Poovendran, University of Washington

James Preston, BAE Systems

Svetlana Radosavac, DoCoMo Communications

Vahid Ramezani, Avyna

Ayan Roy-Chowdhury, Cerona Networks

Nikos Sidiropoulos, Technical University of Crete

Gurdip Singh, i2 Technologies

John Splain, Mitretek Systems

Roshni Srinivasan, Intel

Maria Striki, Telcordia

Xiaobo Tan, Michigan State University

Carole Teolis, TRX Systems

Georgios Theodorakopoulos, EPFL

Andrew Vakhutinsky, Akamai Technologies, Inc.

Sudhir Varma, NIH

Guilherme Vieira, Catholic Univ of Parana, Brazil

Thomas Vossen, University of Colorado

Wei Xi, Western Digital

Qiang Yang, Hong Kong Univ of Science & Tech

Xiaodong Yao, SAS Institute

Enlu Zhou, Univ Illinois Urbana-Champaign

Chenxi Zhu, Fujitsu Labs

Design, Operations, Supply Chain Management

Sundar Balasubramanian, British Telecom

Narender Bhogadi, TransUnion LLC

Antonio Cardone, NIST

Chien Yu Chen, George Mason University

Mandar Chincholkar, Intel Corp.

Duk-Hi Chun, Korean Air Operations Control Central

Stefano Coraluppi, NATO Undersea Research Center

Anindya Datta (unknown)

Robert Day, University of Connecticut

David Delalio, Meso Scale Diagnostics, LLC

Abhijit Deshmukh, Actify, Inc.

Mustafa Eroz, Hughes Network Systems

Sean Gahagan, Northrop Grumman

Ken Gerber, i2 Technologies

Ingar Grev, Raytheon

Ying He, National Institutes of Health

Sara Hewitt, TRW

Ali Hirsa, Caspian Capital Management

Robert Hoffman, Metron Aviation

William Howell, BAE Systems

Jiaqiao Hu, SUNY Stonybrook

Jun Huang, UGS PLM Solutions

Tasha Inniss, Spelman College

Sivaramakrishana Iyer, Honeywell

Tachyung Kim, Korea Transport Institute

Scott Laprise, BAE Systems

Feng Lee Lin, National Sun Yat Sen University

Vidit Mathur, Verizon

Julie McNeil, General Dynamics

Avijit Mukherjee, NASA Ames Research Center

Dung Hanh Nguyen, Lockheed Martin

Vera Osidach, Centers for Disease Control

Gurdip Singh, i2 Technologies

John Splain, Mitretek Systems

Andrew Vakhutinsky, Akamai Technologies, Inc.

Guilherme Vieira, Catholic Univ of Parana, Brazil

Thomas Vossen, University of Colorado

Qiang Yang, Hong Kong Univ of Science & Tech

Xiaodong Yao, SAS Institute

Enlu Zhou, Univ Illinois Urbana-Champaign

Neuroscience and Biology-Based Technology

Bill Byrne, University of Cambridge

Maria Chait, University College London

Mounya Elhilali, Johns Hopkins University

Kaushik Ghose, postdoctoral researcher, Harvard University

Raul Rodriguez-Esteban, Boehringer Ingelheim

Victor Grau Serrat, Massachusetts Institute of Technology

Yadong Wang, Ditech Networks

Micro and Nano Devices and Systems

Yuhong Cai, Intel Corp.

Hsiao-Yung Chang, Novellus Systems

Jing Chen, Tufts University

Soon Cho, Intel Corp.

Jae Ouk Choo, Samsung

Wen-Hsien Chuang, Intel Corp.

Brian Conaghan, Intel Corp.

Melissa Considine, Northrop Grumman

Erin Dreyer, JHU APL

Nima Ghalichechian, Form Factor, Inc.

Colby Goodloe, NASA Goddard

Nayanee Gupta, Intel Corp.

Brendan Hoffman, Newell Rubbermaid, Inc.

Stephan Koev, NIST

Wei Lei, Novellus

Benjamin Levy, Sensis Corp.

Yi-Hung Lin, Intel

Xiaolong Luo, BioE

Alireza Modafe, Synaptics, Inc.

Brian Morgan, ARL

Rinku Parikh, Solers, Inc.

Israel Perez, UC Irvine

Marcel Pruessner, Naval Research Laboratory

Ramaswamy Sreenivasan, MIT

Yani Liu Wong, Virage Logic

Theresa Valentine, Nuclear Regulatory Commission

Yiheng Xu, IBM Microelectronics

Computing, Speech, Artificial Intelligence, Data Mining

John Barnett, SAIC

Chaitali Chakrabarti, Arizona State University

Victor De Oliveira, University of Texas San Antonio

Alexios Delis, University of Athens

Kutluhan Erol, Mindlore, Inc.

Konstantinos Fokianos, University of Cyprus

Naresh Gupta, Adobe Systems, Inc.

S.K. Gupta, University of Maryland

Neal Jeffries, NIH

Brian Johnson, eBay

Hyunchul Kang, Chung-Ang University

Raghu Karinthi, Cisco Systems, Inc.

Ta-Hsin Li, IBM TJ Watson Research Center

Jaime Montemayor, JHU APL

Sashidhar Narahari, Riversand Technologies

William Regli, Drexel University

Yiannis Sismanis, IBM Almaden Research Center

Steve Smith, Great Game Products

Zhexuan Song, Fujitsu Laboratories of America

Scott Thompson, Penn Diagnostics

Dimitrios Tsoumakos, NTUA Greece

Reiko Tsuneto, Space Telescope Science Institute

Qiang Yang, Hong Kong Univ of Sci and Tech

Panayiotis Zaphiris, London School of Informatics