The Final Report to the National Science Foundation

of the Institute for Systems Research

Gary W. Rubloff, Director

Steven I. Marcus, Director 1991–1996

John S. Baras, Founding Director, 1985–1991

ISR is a permanent institute of the University of Maryland, within the Glenn L. Martin Institute of Technology/A. James Clark School of Engineering. It is a National Science Foundation Engineering Research Center.

ISR develops, applies and teaches advanced methodologies of design and analysis to solve complex, hierarchical, heterogeneous and dynamic problems of engineering technology and systems for industry and government.

Second floor, A.V. Williams Building, University of Maryland, College Park, MD 20742
***Phone** 301-405-6632, **Fax** 301-314-9920, **E-mail** isr@isr.umd.edu, **Web** www.isr.umd.edu*

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Context of the ERC in systems engineering

State of the art before the ERC was established

Systems methodology as we know it today was profoundly influenced by the work of Norbert Wiener in the 1940s and 1950s. His ideas about "cybernetics" provided a unified framework in which problems of both control and communication (and later, computing) could be addressed. He promoted the approach of building models not tied to a particular piece of equipment; the idea was to replace a complicated dynamic system by an object, such as a transfer function, that abstracts the behavior in a useful way and hides the details of implementation.

This basic idea of systems thinking is a key idea in control, communications and computer science. Another milestone was the work of R.E. Kalman in the late 1950s, whose Kalman filter and linear-quadratic regulator were ideally suited for digital computer implementation and resulted in successful aerospace applications.

There were significant advances in the 1960s in linear systems, and in the 1970s and early 1980s in multivariable control theory and in adaptive control. However, these research accomplishments remained to be translated into effective design tools that would enable their application to engineering systems. Mathematical models and algorithms had been derived for nonlinear signal processing and filtering problems, their implementation in software and computer hardware had not yet been considered.

In 1985, before the establishment of this Engineering Research Center (ERC), control and systems engineers had few tools with which they could apply advanced methodologies. Traditional control and systems methodologies were applicable to relatively simple systems, so engineers took established (simple) models "over the wall" and used these techniques, possibly after applying straightforward model reduction algorithms. Control design was not at all integrated with other elements of design as an interactive, iterative process.

There was little emphasis on modeling and experimental components in the systems field, particularly in universities. System development was ad-hoc, with little in the way of formal modeling and analysis tools. Developments in computer science and VLSI had little impact on control and communication system design. There was little automated control or communication system design software. The methodology in systems design had not kept pace with the technological developments in microelectronics, computer-aided design (CAD) and artificial intelligence (AI).

Contributions of others to systems engineering during the ERC funding period

The technical elements which comprise systems engineering, such as methodologies for intelligent control, optimization techniques, or scheduling and operations, have been the purview of independent investigators in numerous universities for some time. However, there have been few coherent research programs that effectively integrate multiple components of systems engineering advances. Since ISR's establishment in 1985, other broad research programs in systems engineering have included the MIT / Harvard / Brown Center for Intelligent Systems (funded by the Army Research Office) and a number of efforts at the University of California at Berkeley, including the PATH intelligent transportation project and the Integrated Approach to Intelligent Systems MURI (also funded by ARO).

ISR's significant advances in knowledge and technology

Since its inception, ISR has been at the forefront of the progress made in systems research and applications. Methods from computer science have begun to be integrated with those from control and communications and software tools for design have become prevalent. ISR has made great progress in advancing the state of the art in control, communications, and computation, and in the integration of these fields for the design of complex dynamical systems. These advances cover the full spectrum: from fundamental research to implementation in hardware and software to the use of these advances in industry. The advances have moved the systems field significantly in the direction of formal modeling, analysis and optimization-based techniques. They represent a real advance in the state of the art.

Intelligent Control. There have been significant advances in the study of linear and nonlinear systems described by differential equation models, including methods for stability analysis, optimization, robust control, adaptive control, stabilization, tracking, and sensitivity minimizing controllers. ISR has been at the forefront of exciting developments in nonlinear control theory and design principles for designing nonlinear control systems.

Little work has been done to extend this significant body of control results to heterogeneous systems. The complexity of systems is increasing faster than our ability to analyze and control them.

Recently ISR has played a major role in a strong effort to model and understand hybrid models for heterogeneous systems involving both numeric and logical variables. Such models arise in many contexts, including multi-mode systems that are reconfigurable or have failure modes, disk drives, robotic systems, and stepper motors. These models involve a close coupling between parts that are governed by differential equations and parts that are governed by models from computer science such as finite state automata. We have developed new analog models for hybrid systems at ISR, as well as a hybrid control formalism based on MDL, our device independent motion description language. Our aim is to develop methodologies based on these advances which will lead to knowledge and tools for the control of heterogeneous systems.

Signal Processing and Communication. Communication and information processing are critical components of system operation. At the same time, the communication infrastructure of a system itself constitutes a subsystem that must be controlled. Although this coupling between control and communications has been widely recognized, there has been little progress in exploiting it to enhance overall performance. In large communication systems such as communication networks, control methodologies have been used to some degree. ISR has been a leader in this effort.

Networking and signal processing aspects of these systems have traditionally been pursued separately, despite the strong interaction between them. ISR has been at the forefront of current trends that have begun to combine signal processing techniques, such as compression, with networking techniques, such as broad band switching, for joint design that integrates across traditionally separate network layers.

ISR has been a leader in the key area of hybrid satellite, terrestrial, and wireless telecommunication networks. There have been significant contributions at ISR to network performance evaluation and design. This effort has led to the establishment of the Center for Satellite and Hybrid Communication Networks (funded by NASA) at ISR and the participation of ISR as a key partner in the Advanced Telecommunications and Information Distribution Research Program (a Federated Laboratory of the Army Research Laboratory).

Furthermore, ISR has initiated the full exploitation of this coupling between communication and control by considering the impact of communication technology on control design. Instances in which the coupling has yet to be fully exploited include the reliance of control strategies on sensor technology and data fusion, the effects of signal compression techniques on servo loop bandwidth, and the use of hierarchical signal representations (such as progressive coding and compression) both for adaptive network flow control and for improved operation of control systems in general.

Systems Integration Methodology. There is a need for a rational methodology for solving problems of systems integration; this was a clear message of ISR's December 1994 Industry Workshop. There is a considerable body of knowledge on object-oriented programming and object-oriented databases, and there has been progress in describing products with higher level codes.

However, no methodologies exist for representing processes in an object-based manner at a higher level of abstraction. These are not just computer science or software issues. They require, for example, a close coupling with research on modeling. ISR has been a leader in the development of fundamentals for heterogeneous databases and deductive databases. Complexity has been studied for some classes of models, but quantitative theories of model complexity for heterogeneous systems do not exist.

The use of feedback to manage system complexity has been studied extensively, but systematic efforts to make quantitative comparisons between architectures for heterogeneous systems have been lacking. ISR has been at the forefront of research on optimization and trade-off analysis based on linear and nonlinear optimization. This has culminated in widely used tools such as CONSOL and FSQP.

Progress has been made at a number of universities on mixed integer-nonlinear programming. However, there is a clear need for tools and methodologies for analyzing trade-offs between conflicting specifications and performance metrics for complex heterogeneous systems. ISR has been a leader in AI planning (including heterogeneous planning), and is now beginning to combine these methods with optimization-based techniques to perform trade-off analysis for heterogeneous systems.

Impact of ISR research advances on systems engineering

In 1985 the main research theme and vision of this ERC 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:

- In-depth investigation of the impact of VLSI, CAD, and AI;
- Fundamental research in modeling, optimization, computational and numerical methods
- Techniques for control systems, communication systems, and computer engineering;
- A set of five application thrust areas, including intelligent CAD of stochastic systems, intelligent

servomechanisms, chemical process control, advanced automation and information processing in manufacturing systems, and telecommunication systems.

When ISR was founded, a significant amount of control and communication research was being undertaken in universities, and a significant amount of control and communication practice was occurring in industry, but there was little connection between the two.

There was a clear need for a cross-disciplinary center to bridge this gap. ISR's goal was to change the situation by:

- Bringing experiments and industrial interactions into the university and its education and research programs;
- Educating a new breed of engineer who would have a broad as well as a deep foundation, and an understanding of industrial practice;
- Bridging the gaps between disciplines; and
- Transferring technology to industry.

ISR has been successful in all aspects of its programs: education, cross-disciplinary research and technology transfer and industrial interaction. It has been a major force in changing the paradigm for the way in which systems research and education are carried out. Universities around the world have adopted ISR's approach of combining theory and experiment in communication and control. ISR's focus on integrating control, communication and computation also has been validated and adopted.

Impact on industry

ISR has had a profound influence on industry during a time of two fundamental and important changes.

First, industry has identified and emphasized a growing need for systems engineering due to increased technological complexity, emphasis on competitive manufacturing, and business forces which place a premium on systems-level design, realization, metrics, rapid time to market and quality.

Second, these pressures have driven corporations to transform the character of their investment in university research from relatively open-ended fundamental work to more directed, coherent, strategic initiatives.

Accordingly, ISR began emphasizing sponsored joint research with corporations, as long as that research was consistent with ISR's overall theme. It also began forming research consortia to diffuse the cost of research while at the same time ensuring corporate participation in that research. The NSF core funding, in this regard, has served as an excellent source of "seed money" to encourage industry to join these consortia.

ISR also began forming and joining consortia to pursue third party sources of funding to underwrite the cost of research; these have included funding from federal agencies as well as state programs such as the Maryland Industrial Partnerships (MIPS). As a result, ISR's collaborations with industry have increased and deepened. Particularly notable have been:

- The emergence of consortia that ISR has organized or been involved in (e.g., the Center for Satellite and Hybrid Communication Networks and the Smart Materials Manufacturing consortium);
- A significant increase in the number of joint ISR/industry projects funded by the Maryland Industrial Partnerships program; and
- More aggressive marketing to industry of ISR's systems approach.

ISR and its industrial partners promote the growth of American industrial competitiveness by accelerating the rate at which fundamental engineering advances are applied by industry. ISR achieves this goal by continuously and actively engaging industrial partners in every level of activity in the organization, and, by doing so, promoting the rapid exchange of information between ISR and those industries. During its existence, the number of patents and copyrights issued to ISR has increased, the amount of intellectual property licensed to industry has grown, and the level of industrial participation in ISR activities has expanded significantly.

We present here some examples of the significant impact that ISR has had on industry.

Optimization-based engineering design

ISR has developed two optimization software packages in use at more than 300 sites in 34 countries. CONSOL and FSQP are software packages for interactive optimization-based design of a large class of engineering systems. Each systematizes trade-off analysis in design of dynamical systems, allowing engineers to interactively assess design decisions free from mathematical complexities.

Northrop Grumman has incorporated CONSOL into PROTO-OPT, an advanced graphical optimization-based control system design software. At Northrop Grumman's Electronic Sensors and Systems Division (ESSD), CONSOL is being implemented to design a line-of-site stabilizer for an airborne camera. At General Electric, FSQP is incorporated in Engineous for design optimization and automation, yielding a 10 to 1 productivity savings for the company. Texaco is using FSQP in its process control software, now being commercialized, for nonlinear constraints and feasible iterate.

Next generation network management system

ISR and Hughes Network Systems (HNS) have been participating in a collaborative research and development effort to develop the next generation network management product for satellite and hybrid network configuration management. The project incorporates ergonomically designed graphical user interfaces tailored to the network configuration management function and advanced object-oriented database structures.

The design concept incorporates object-oriented programming methodology to associate data with functions, permit customization and provide an open architecture environment. Hughes Network Systems strongly believes that the resulting network management product will help the company maintain a strong, long-term competitive position relative to foreign competitors, improve its exports and increase its revenues by tens of millions of dollars.

Producability and manufacturability of high power surveillance T/R modules

High Power Surveillance Transmit / Receive modules are an integral part of the latest active aperture surveillance radar antenna arrays being developed and manufactured by Northrop Grumman ESSD. Since 1991 ISR has worked with engineers at ESSD to develop an expert software system to optimize design configuration and manufacturing processes for the production of High Power T / R modules.

Information technology has been used to create a unique concurrent engineering environment for design and manufacturing of electronics products. The developed system consists of an object-oriented database, a cost evaluation module, a quality evaluation module and a process planning module. It is capable of analyzing a given process plan based on the system's knowledge and user input and is able to critique the plan in terms of cost, quality and manufacturability. This computer-based system has been installed at ESSD and is currently being used as a consultation tool to management and engineers seeking the most cost-effective approach to producing T / R modules while maintaining high quality.

Facility design

ISR has developed a master plan for shop layout that is expected to yield $300,000 cost savings during the second phase of implementation at Northrop Grumman ESSD. In the company's manufacture of radar assemblies, over 10,000 parts are produced in a job shop facility that comprises 160 work centers arranged in a functional layout. The shop layout causes high part traffic and, consequently, large production cycle times.

To improve efficiency, ISR researchers adopted a three-stage approach to the redesign:

- Determined a set of manufacturing cells based on the inter-resource traffic; computed the expected savings in material movement; selected the most promising of these cells for implementation;
- Derived a layout that maximized the flow in a common direction for the machines in each of the previously selected cells (a variety of cellular arrangements were examined); and
- Derived a time-phased implementation plan to decide which cells should be implemented, the time at which the implementation will take place and the final layout of machines and cells on the facility shop floor; the goal was to maximize the total benefits over time while keeping machine relocation costs within budget constraints.

A software package that performs all of the above design modules is being developed.

Disk head control

ISR and Digital Equipment Corp. jointly developed a new control algorithm for positioning the read-write head on a high-performance disk storage unit. ISR researchers used a digital controller and a specially parameterized torque profile, chosen to approximate a bandlimited function, to accomplish the positioning operation more rapidly. With present methods for this procedure the control forces applied to the positioner excite vibratory modes in the positioning arm and only when these vibrations die out can the read / write operation be performed. ISR's scheme eliminates higher harmonics from the input and from the resulting motion of the positioning arm, making it unnecessary to allow for a delay while they die out.

Design of a smart tool post for precision machining

Smart materials are critical for the creation of structures that can sense and react to their environment. This project explores the application of smart materials in machine tools for vibration compensation. ISR worked with three industrial partners

(Martin Marietta Laboratories, Lockheed and AVX) to design a tool post for precision machining.

In the product design, multi-layer stack-type actuators made of an electrostrictive lead-magnesium-niobate (PMN) ceramic material were used as built-in devices to provide anti-vibration action during machining. A product prototype of the tool post has been fabricated at ISR to demonstrate the systems engineering approach for product development.

In the mechanical design, the principle of vibration absorption was employed and membrane components were used to maximize the authority of the actuators for vibration compensation. In the controller design, the method of self-tuning control has been used to coordinate the actuator excitation based on detected tool vibration. The prototype is now under testing. ISR is now working with its industrial partners for commercialization of the smart tool post product.

Impact on research

The Institute for Systems Research serves as an instrument of change at both Maryland and Harvard, particularly concerning attitudes about cross-disciplinary research, education and interaction with industry. ISR is a new type of institute that stresses truly cross-disciplinary research, working in teams and the importance of working closely with industry.

ISR has been held up as a model for combining cross-disciplinary research, education and public service by the Deans of Engineering and Computer, Mathematical and Physical Sciences, the Provost and the President of the University of Maryland, as well as by the University of Maryland System Blue Ribbon Committee on Research and Public Service.

The value system among faculty (both inside and outside ISR) has been changed as a result of ISR's influence: working with industry and working in cross-disciplinary teams are now regarded as key elements of a faculty member's responsibilities. Indeed, these factors are taken into account in promotion, tenure and merit raise decisions; the ISR director has an official role in these processes for faculty with joint appointments in ISR.

Since ISR's inception, there has been a distinct improvement in the extent to which engineering systems research at Maryland and Harvard is relevant to industry and in the tendency of faculty and students to work in teams that include industry. Many of ISR's projects now involve faculty from a number of the 12 departments affiliated with ISR. In addition, the choice of research directions has increasingly been influenced by relevance to industrial needs.

Interactions of faculty and students are enhanced by the co-location of the primary offices of most ISR faculty in ISR space and by a student office policy that places students from different departments in the same office. This bringing together of faculty and students from different departments has broken down departmental barriers.

ISR faculty have spun off two centers built on ISR's model of industrial interaction and cross-disciplinary research. These are the CALCE Electronic Packaging Research Center (an NSF State / Industry / University Cooperative Research Center) and the Center for Satellite and Hybrid Communication Networks (a NASA Commercial Space Center). Each includes a consortium of companies; the latter includes other universities as well.

Because of ISR's success and because many of the administrative problems associated with cross-disciplinary research have been worked out between ISR and the departments, there has been an increasing number of cross-disciplinary proposals funded and centers established at the University of Maryland and led by ISR faculty. These include the Center for Auditory and Acoustic Research (funded by the Office of Naval Research), the Center for Dynamics and Control of Smart Structures (funded by the Army Research Office), the National Center of Excellence in Aviation Operations Research (funded by the Federal Aviation Administration), the program in Collaborative Agent Technology Systems (funded by the Army Research Laboratory), the program in Learning and Intelligent Systems (funded by the National Science Foundation), and the program in Operational Methods for Semiconductor Manufacturing (funded by NSF and the Semiconductor Research Corporation).

These programs represent embodiments of integrated systems research approaches, some aligned more toward application areas and others toward advancing fundamentals in systems research. NSF's ERC investment in fundamental systems research themes has thus flourished, leading to a kind of federation of major programs and activities which reflect the initial systems engineering core. At this point, ISR has become a highlight of engineering at the University of Maryland, integrally connected to almost one third of its portfolio of engineering research. Furthermore, ISR is regarded as—and is encouraged to be—the primary leader for cross-disciplinary initiatives in the College of Engineering.

Impact on education

The Institute for Systems Research has implemented a comprehensive education program that spans the spectrum from post-doctoral researchers to elementary and middle school students. These programs have had a profound effect on the engineering education provided by the University of

Maryland and Harvard and their influence has spread well beyond those campuses. For example:

- From 1988 through August 1997, 238 Ph.D. students and 410 M.S. students from the University of Maryland closely affiliated with ISR have received their graduate degrees. In that same period of time Harvard graduated 19 Ph.D. students closely affiliated with ISR. In addition, 129 ISR-affiliated B.S. students at Maryland and one at Harvard have graduated.
- Since 1985, 246 undergraduate students—not only from the University of Maryland and Harvard, but from other schools as well—have carried out research under the aegis of ISR.
- ISR established a graduate degree—the M.S. in Systems Engineering (MSSE)—in 1987. There have been 49 graduates through spring 1997; 25 students are currently enrolled.
- ISR has sponsored a "Young Scholars" program every summer since 1991; thus far this program has brought 146 high-school students to ISR for a six-week program of classroom education, lab experiments and exposure to technological fields. Thirty-three of these students are now studying at the University of Maryland.
- There have been 64 post-doctoral researchers working with ISR faculty at the University of Maryland and Harvard during this time.

Graduate education

The most substantial effects ISR has had on engineering education at the University of Maryland and Harvard have come at the graduate level. These effects come primarily from two closely related sources: the cross-disciplinary nature of ISR's faculty and research and ISR's establishment of the M.S. in Systems Engineering.

With faculty and students dispersed over 11 departments and four colleges at the University of Maryland and Harvard's Division of Applied Sciences, the breadth of expertise and methodologies that ISR can bring to bear on a systems-related problem is unique. This cross-disciplinary nature is reinforced by the structure of ISR's research program-with multi-departmental teams organized around broadly defined thrust areas and research projects.

ISR's cross-disciplinary nature has had a great impact on the graduate education programs at the University of Maryland and Harvard. 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.

The M.S. in Systems Engineering (MSSE) graduated its first student in 1990; it has consistently grown in both size and quality since then. 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;
- Instill an understanding of the financial and management issues associated with complex engineering systems; and
- Provide a deep understanding of one particular application area.

The curriculum of the MSSE was designed with substantial industry input; furthermore, it represented the first multi-college graduate degree program at the University of Maryland involving the engineering college. Subsequent programs that followed the MSSE model include an M.S. in Telecommunications and a proposal for an M.S. in Manufacturing. ISR faculty have played key roles in the development of both of these programs.

Undergraduate education

ISR has affected undergraduate education at the University of Maryland and Harvard primarily through curriculum innovation and exposure to research.

The development of the ***Walking Machines*** course at the University of Maryland is an archetypal example of an ISR innovation involving both curriculum enhancement and undergraduate involvement in research. This senior-level course uses a three-year cycle to investigate all the issues associated with designing and building a walking robot with navigational capabilities; different semesters focus on issues such as control, power, gear mechanisms and signal processing.

The course has been designated a "capstone design course" in both electrical and mechanical engineering—the only course at the University of Maryland to be so designated in two different departments. Moreover, the "Walking Machines" course is part of a combined undergraduate / graduate effort to create a research testbed for robotic design; undergraduates get direct involvement in ISR-related research. Since its inception in 1991, close to 200 undergraduate students have taken this course.

At the end of each course, an autonomous robot "grand prix" is held according to international rules. In 1997, the winning team from Maryland traveled to Tokyo and competed against more than 100 mostly Japanese robots. The Maryland robot "Lancelot" won, and its creators became instant media celebrities. Their story appeared on the front page of The Washington Post, on Good Morning America, on public television, and in many other news outlets.

ISR administers the innovative, interdisciplinary ***Gemstone*** undergraduate honors program, originally conceived by William Destler, Dean of the A. James Clark School of Engineering. Gemstone addresses two of the most common criticisms of modern undergraduate education—the lack of an integrative experience to provide a context for learning, and the failure to provide meaningful interactions between students in different disciplines.

As freshmen, students form teams and spend their next three years analyzing and investigating important societal problems from various disciplinary perspectives. Now in its second year, the program has attracted nearly 300 students, with average SAT scores of 1440. University officials hope the Gemstone concept will help Maryland stake out a national presence as a leading innovator in undergraduate education. ISR was chosen to administer the program because of its experience and reputation in bringing together faculty and students for cross-disciplinary research.

The changes in ***freshman engineering design courses*** are another example of the influence of ISR on undergraduate curriculum. Working with the NSF-sponsored ECSEL coalition, ISR faculty have been instrumental in revising the University of Maryland course. The revamped course is centered on a real engineering design project undertaken by small teams of students; projects have included windmills, human-powered pumps and solar cookers. The enthusiasm generated by this course has already resulted in a substantial reduction in engineering student attrition. In 1997 Associate Professor Guangming Zhang (ME / ISR) took over the leadership of ECSEL at Maryland, succeeding Thomas Regan, Associate Dean of the A. James Clark School of Engineering, who then became director of the overall ECSEL coalition.

A similar freshman design experience has been implemented at Harvard by Professor Roger Brockett and the result is a clear example of how the two-university nature of ISR can be used to test similar kinds of educational reforms in two different kinds of educational environments.

ISR has dramatically increased the number of undergraduate students conducting ***systems-related research*** at the University of Maryland. Many projects central to ISR's mission have had substantial undergraduate involvement.

Undergraduate research has been supported primarily through two programs. The ***Research Experience for Undergraduates*** (REU) program has been sponsored by NSF since 1987. It offers stipends to undergraduates from other universities to come to ISR to work on research projects over the summer. More than 113 students from 50 different schools have conducted research at ISR under this program. The ***Systems Undergraduate Research Fellowships*** (SURF) program is funded by the Institute for Systems Research using state funds. This program pays a stipend to undergraduates at the University of Maryland who work on ISR research projects, either during the summer or the academic year. ISR has supported 53 students in the SURF program since 1991.

The REU and SURF programs are not the only means by which undergraduates participate in ISR research. Dozens of students have taken "projects" courses during which they worked on research and development tasks under the guidance of ISR faculty and graduate students.

Outreach to pre-college students

ISR has run an NSF Young Scholars program since 1990. Each year, 25 pre-senior high-school students have spent six weeks of the summer at the Institute. Their time on-campus has been broken up into three activities:

- Taking ENES 100 (Introduction to Engineering Design), the course described earlier in this section under "Undergraduate Education," for which they earn three credits;
- Spending several afternoons each week in an ISR-affiliated laboratory; and
- Attending a wide array of seminars, field trips and workshops

The Young Scholars program has been extremely successful, praised by students, parents and teachers alike. Moreover, followups show that of the 146 Young Scholars in the first four years of the program, 90 of them are currently pursuing degrees in engineering or science, 33 at the University of Maryland.

Outreach to working engineers

ISR has been active in generating short courses relevant to industry. In 1996 ISR faculty members conducted a four-part short course on systems engineering at the NASA Goddard Space Flight Center. During 1993 and 1994 ISR began an effort in distance education that resulted in a series of short courses on systems engineering being delivered to 10 United Technologies sites via interactive compressed video. In addition, ISR began offering a Professional M.S. in Systems Engineering in Fall 1994. It is an applications-oriented, methods-focused part-time graduate program designed primarily for working engineers.

Post-doctoral appointments

As an international resource in systems science and engineering, ISR hosts a large number of post-doctoral researchers from other institutions. They are exposed to unique opportunities and a rich research environment, and are substantial contributors to our research program. The number of post-doctoral researchers working at ISR has grown continually as ISR has matured. There were 14 ISR postdocs in the 1997-98 academic year.

Diversity

The Institute for Systems Research has made a strong commitment to increasing the diversity of its participants (locally) and that of the engineering profession (globally). Of the 49 graduates of the MSSE program, 14 (28 percent) have been women and 10 (20 percent) have been from under-represented minority groups, i.e., African Americans and Hispanics. A snapshot of the 24 students enrolled in the MSSE program during the 1997-98 academic year reveals that 5 (20 percent) are African American or Hispanic, while 6 (25 percent) are female.

Of the 146 Young Scholar participants, 65 (45 percent) have been female, and 27 (18 percent) have been from under-represented minority groups.

Of the 113 REU participants since 1987, 30 (26 percent) have been women, and 23 (20 percent) have been African American.

ISR recognizes that more needs to be done to make better use of the talents of all of America's potential engineers and scientists. One of ISR's goals is to become a focal point for diversity initiatives in the College of Engineering at the University of Maryland.

Consequences and the future of the ERC

Employment history of ERC graduates in industry

ISR's database includes information on 277 alumni and their current employers. ISR alumni are working in telecommunication, satellite, computer, manufacturing, defense, automotives, consulting, government and military settings. Some include:

Employer	No. of ISR graduates
AT&T Bell Labs	7
Bellcore	6
COMSAT	5
Comsearch	4
General Electric	2
General Motors	2
Hughes Network Systems	12
IBM	17
Johns Hopkins Applied Physics Lab	10
Lockheed Martin	3
MITRE	4
Motorola	3
NASA Goddard	4
Naval Research Lab	7
Texas Instruments	3
TRW	3
Westinghouse	4

Lessons learned

Once the ERC was funded by NSF with significant university support, the founding Director John Baras undertook two efforts key to long-term viability. First, he established a leading-edge center for telecommunications (initially, the NASA Center for the Commercial Development of Space, or CCDS) within the ISR, which brought together a spectrum of ISR skills in systems research in a coherent way. This 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, Baras used the 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 throughout the life cycle of an ERC.

Additional information on this topic is available. John Baras was interviewed extensively for the 1997 NSF *Engineering Research Centers Best Practices Manual*, which is available online at http://www.erc-assoc.org/.

The future of the Institute for Systems Research

ISR will persist as a viable and vital entity in several ways.

First and foremost, it will remain the protagonist for cross-disciplinary, systems-directed research in at the University of Maryland because of its intellectual leadership and the growing importance of systems engineering.

Second, ISR will continue as a result of its permanent state funding and Institute status within the University of Maryland system. Its management structure, now formalized through the Institute's Constitution and Bylaws, will also persist.

Third, the structure of research contributions will continue with ISR's evolution. Fundamental systems problems correctly continue to be thought of in terms of research thrust areas in control, communications and signal processing and systems integration, i.e., the heart of the ERC's research program and thrust area organization. To complement this, the investment of research efforts in systems problems organized by their area of application will continue as well. Increasingly these will drive the major funding opportunities for ISR's research agenda. The notions of concentrating on major, enduring themes of systems research and realizing them through applications testbeds is consistent with the ERC organizational concept.

Fourth and finally, the educational program will be maintained in several forms. The M.S. in Systems Engineering, as well as the corresponding Professional Master's degree, are already part of the university's degree programs; furthermore, dramatic demand for systems engineering education will provide a strong incentive for current efforts to revise, improve, and disseminate these unique programs. Similar excitement stems from ISR's Gemstone program at the undergraduate level; this has not only captured tremendous attention across the campus and nation, but it has stimulated thinking in ISR about mechanisms to bring systems educational experiences to a broad spectrum of undergraduates, both in and outside engineering. And with the support of the state, ISR hopes to continue its support of other educational programs. ISR's future research agenda will continue to be realized through its evolution into a federation of centers and major research programs under the Institute umbrella and supported by the ISR staff and funding. Currently with six such large activities, ISR is now focusing on how a synergistic relationship can be structured among ISR, its centers and large programs. The arrangement must recognize and support the thematic and structural diversity of the centers as well as the pervasiveness of fundamental systems methodologies throughout the centers.

Another aspect of ISR's future concerns its outreach to new areas of opportunity. ISR has achieved excellence and recognition for its contributions and talent in key areas central to systems research. These can leverage additional benefits through new associations with other disciplines and research areas in the College of Engineering, information technology, and a host of external representatives from industry, government, and academia. Examples of such opportunities include reliability and risk assessment, transportation, civil infrastructure systems, economics and finance, environmental systems, and learning systems.

The College Park campus provides profound faculty resources to underwrite such initiatives, while research needs assessments and agendas on the national scene highlight directions of high potential. ISR's educational activities will remain a very high priority. With focus on systems research as seen from the perspective of both core systems skills and systems applications, the educational experiences of students and postdocs directly involved in ISR's research programs will continue to deliver substantial and unusual value as these alumni move into careers in industry, government, and academia.

Significant portions of ISR's educational programs from pre-college to continuing education will continue, providing rich new insights to students about the nature of engineering, the importance of cross-disciplinary viewpoints, and the central role of systems engineering and thinking. Some of these (e.g., Young Scholars, REU, and the Masters' programs in systems) are now established vehicles. At the same time, the Gemstone program for honors undergraduates, as well as contemplated new undergraduate and graduate programs in systems represent outstanding leadership in broader engineering education. These will remain a high priority for ISR.

ISR's Masters programs in systems engineering represent an outstanding opportunity for major contribution. While industry and government increasingly and forcefully underscore the profound needs for both regular academic and continuing education in systems engineering, few opportunities currently exist nationwide. ISR is encouraging and supporting major developments in its systems engineering education programs along several directions, including: construction of modular components accessible over the Internet and usable for customized short courses; increased emphasis on case studies and the application of systems engineering tools; collaboration with industry and government practitioners of systems engineering; and development of a graduate certificate program in systems engineering which would accompany advanced degrees in conventional engineering disciplines.

Past successes of ISR as an ERC provide a sound platform for significant further growth in the future, with emphasis in three directions: (1) systems research; (2) systems engineering education; and (3) expansion of ISR's contributions to new domains of systems engineering. This exciting future could not have happened without the combined visions of leaders in ISR and NSF.

The Institute for Systems Research

Second floor, A.V. Williams Building, University of Maryland, College Park, MD 20742
Phone *301-405-6632,* ***Fax*** *301-314-9920,* ***E-mail*** *isr@isr.umd.edu,* ***Web*** *www.isr.umd.edu*