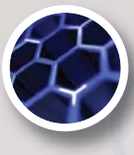














SYSTEMS ENGINEERING
Research Center

2010 ANNUAL REPORT

A US Department of Defense
University Affiliated Research Center

SYSTEMS ENGINEERING
Research Center

Systems Engineering

2010 ANNUAL REPORT

CONTENTS

Making the Magic Happen

Our world is overflowing with technological miracles, bordering on magic, created by the incredible rate of technology advancement, and the interconnection of thousands of disparate systems. They measure and track and correct us with little interest or understanding on our part. Global Positioning System (GPS), financial markets, mobile internet, air traffic control, social networking, credit/debit cards, and anti-lock brakes are only a few functions enabled by complex systems of systems. We depend on these systems with little or no conscious concern about their correct behavior. More important, the problems we face on a global scale will require the understanding of systems and solutions that are possibly more complex than we have ever imagined.

Systems engineering is a multi-disciplinary practice that uses a holistic, systems approach to make sense of and manage the complexity of problems and solutions. It makes sure created systems meet the needs of the stakeholders and don't outrun our willingness to accept the risks associated with the benefits.

"Any sufficiently advanced technology is indistinguishable from magic."

Arthur C. Clarke

Rarely do such complex systems have a closed-loop, predictable life cycle, and the rate of change and the complexity of the systems are outpacing the ability of systems engineers to fulfill their role. In fact, the term "life cycle" is probably more appropriate than ever; these systems aren't so much built, but rather grow and evolve, their new capabilities emerging as a result of advancing technology and expanding interconnectivity.

The Systems Engineering Research Center provides a critical mass of researchers across 20 US universities and research institutions. It is creating new methods, processes, and tools that will enable systems engineers to understand increasingly complex problems, and to design and build solutions within reasonable cost and schedule constraints.

Critical problems requiring a systems approach:

Terrorism

Cybersecurity

Climate Change

Transportation

Health Care

Director's Message

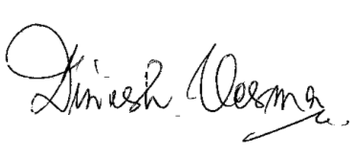
Dinesh Verma, Ph.D.
Director,
Systems Engineering
Research Center

Welcome to the Systems Engineering Research Center (SERC) 2010 Annual Report. The SERC, a U.S. Department of Defense and intelligence community University-Affiliated Research Center in systems engineering research, was competitively awarded to Stevens Institute of Technology in 2008. The SERC currently consists of 20 collaborating institutions led by Stevens.

This has been an exciting and productive year for us, and this report highlights some of our activities and results. We formed the SERC Research Council (see page 3) to accelerate our maturing into a collaborative network of universities scaled for the scope of systems engineering research our sponsors require. Our results enhance the ability to conceive of, define, synthesize, integrate, test, operate, and evolve the complex systems, systems of systems, and enterprises needed to address global issues. The SERC is already a strategic and significant national resource.

Rapid growth, improved outreach, and enhanced visibility were hallmarks of 2010. SERC's depth and breadth is expanding beyond what we had imagined. We are receiving unprecedented demand from other government agencies for leveraging the research reach that the SERC represents. The coming year will bring changes in strategy and governance to facilitate this growth (see page 11).

I am truly excited about our future. I see our progress as a harbinger of game-changing accomplishments as the systems engineering discipline transforms to meet the needs of the 21st century.



What Our Sponsors Are Saying

The Honorable Mr. Zachary Lemnios, *Assistant Secretary of Defense, Research and Engineering*

"Systems Engineering is a critical competency for our nation, fundamental to increasing our productivity and our ability to deliver integrated complex systems. The SERC is providing new tools and technologies that advance the state of the practice in systems engineering, and strengthen this foundation for the Department."

Katrina McFarland, *President, Defense Acquisition University*

"DAU is working with the SERC community in several research efforts. These are focused around improving overall engineering workforce capabilities as well as providing skills acceleration via innovative modeling & simulation based training techniques. Among another areas, these efforts will help support the DoD's overall product affordability initiatives. We look forward to continued engagement with the SERC."

Gary Martin, *Executive Deputy to the Commander U.S. Army Research, Development and Engineering Command*

"The technology that we are providing our warfighters today is far more capable and complex than at any time in history. Engineering the integration of these systems into military capability requires greater reliance on systems engineering discipline and on the development of systems engineering processes that can address our Systems of Systems integration challenges. The SERC provides a great opportunity to leverage the intellect and capability of many great academic engineering institutions to develop, validate, and facilitate the employment of these new engineering skills. RDECOM will sign a formal Cooperative Research and Development Agreement with the SERC in April 2011 that will lay the foundation for cooperative efforts between the SERC team and the RDECOM community. This partnership is an important part of our strategy to expand and enrich the systems engineering competency that will support the Army research, development, engineering, and acquisition communities."

John Whiteford, *Associate Director of Engineering and Chief Systems Engineer, National Security Agency*

"We look to the SERC and its research agenda to help us meet our unique systems engineering challenges: to constantly demonstrate value, always be agile, and consistently keep up with the volume and velocity of our mission space."

Research Strategy

This year has given the SERC increasing insight into the critical research needs of the defense and IC communities. As a result, we have refined our research operations. Our Research Strategy now directly aligns with DoD's key Mission Themes, addressing trends in software-intensive, net-centric, and complex systems, enterprises, and systems of systems. To enable our growing research portfolio, we have established an impressive internal Research Council to oversee and support our research activities. Council members were selected based on their individual credentials, their university's significant participation in SERC research, and their willingness to actively support SERC quality and impact.

Aligning Mission Needs to Research Strategy

Mission Themes	SERC Research Areas
Respond more quickly, flexibly, agilely	Systems Engineering and Management Transformation
Acquire, operate, and evolve large complex systems that have distributed and diffuse governance, architecture, and mission	Enterprise as Systems and Systems of Systems
Increase the pool and capabilities of systems engineers, and instill systems engineering thinking and skills into all engineers	Human Capital Development
Address security challenges in a systemic fashion rather than piecemeal	Trusted Systems

The SERC has adopted the following research strategy to dramatically improve systems engineering capabilities in successfully creating complex, flexible, and evolving systems to meet critical national and global challenges.

SERC leadership has identified four areas of research that directly relate to the sponsor mission thrusts. Affordability and cost-effectiveness are key attributes that must be deeply integrated into each of these four areas. Stronger SE capabilities are a major opportunity area for reducing acquisition cost growth, and for achieving comparable savings in total ownership costs via better system architectures.

Enterprises as Systems and Systems of Systems:

Each DoD/IC Service and Agency, and the DoD itself, is an example of Enterprises as Systems. Such organizations must integrate and evolve multiple portfolios of systems with often conflicting sets of objectives, constraints, stakeholders, and resource demands. Integrating evolving capabilities belonging to multiple, often independently managed enterprises, requires negotiation as well as control. Research will determine foundational SE principles and develop appropriate SE methods, processes, and tools (MPTs).

Trusted Systems:

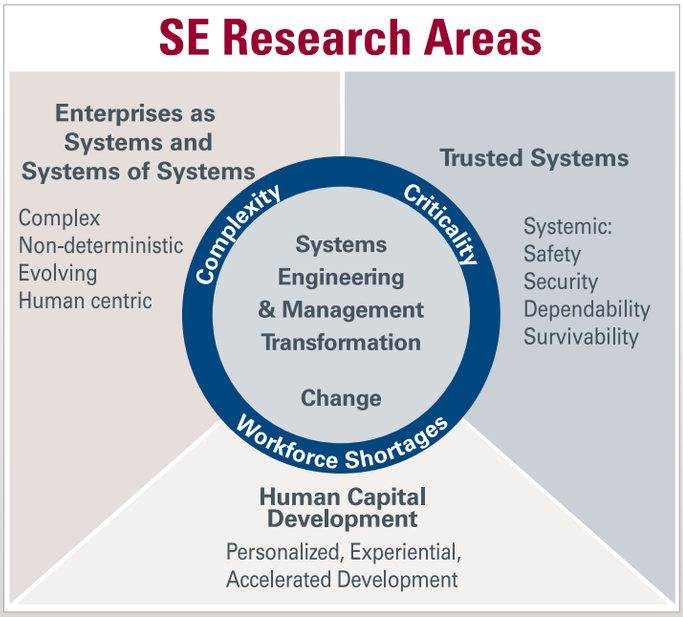
This research addresses challenges in conceiving, developing, deploying and sustaining systems that are safe, secure, dependable and survivable. These emergent properties make it essential to consider the complete system, including human and adversarial elements. Foundational systems principles are needed to ground further research and assure the impact of related MPTs.

Systems Engineering and Management Transformation:

Classical MPTs are too slow, sequential, and reductionist to address the challenges of modern systems: increasing complexity, rapidly changing requirements, radical technology growth, deployment into evolving legacy environments. Deciding how and when to apply different strategies and approaches is as important as the strategies and approaches themselves. This research will create MPTs that leverage the capabilities of computation, visualization, communication, and information technologies to enable rapid, innovative responses to threats and opportunities.

Human Capital Development:

The retirement of the baby boomer generation, the reduced numbers of US citizens entering the technical workforce, and the new systems challenges have made human capital development a critical issue. Research is needed to determine the knowledge and skills required for our future workforce and to create more efficient and effective means to educate practitioners throughout their careers. Example strategies include safe automation of human functions, SE experience acceleration, and continuous career learning.



The SERC Research Council Members

The SERC Research Council, chaired by Professor Barry Boehm, the SERC Director of Research, is formed of leaders in SE research from among the SERC collaborators. The Council is responsible for guiding SERC research strategy and overseeing research quality.

Dr. Barry W. Boehm,
SERC Research Director; TRW Professor of Software Engineering and Director Emeritus, Center for Systems & Software Engineering, University of Southern California

Professor Boehm has been named one of the five most influential thinkers in the field of software engineering for his pioneering research in economics and his creation of the spiral life cycle model. His honors and awards include Guest Lecturer of the USSR Academy of Sciences (1970), the AIAA Information Systems Award (1979), the ISPA Freiman Award for Parametric Analysis (1988), the NSIA Grace Murray Hopper Award (1989), the Office of the Secretary of Defense Award for Excellence (1992), the ASQC Lifetime Achievement Award (1994), the ACM Distinguished Research Award in Software Engineering (1997), the IEEE Harlan D. Mills Award (2000), and the IEEE Simon Ramo Medal for Excellence in Systems Science and Engineering (2010). He is a fellow of the primary professional societies in computing (ACM), aerospace (AIAA), electronics (IEEE), and systems engineering (INCOSE), and a member of the National Academy of Engineering.

Dr. Abhijit Deshmukh,
James J. Solberg Head of Industrial Engineering and Professor of Industrial Engineering, Purdue University

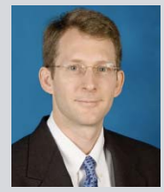
Prior to coming to Purdue, Dr. Deshmukh was the Rockwell International Professor and director of the Institute for Manufacturing Systems at Texas A&M University. He was a professor of Mechanical and Industrial Engineering at the University of Massachusetts Amherst from 2004-2007, and served as a program director in the National Science Foundation (NSF)'s Engineering Directorate and the Office of Cyberinfrastructure. He is a fellow of the Institute of Industrial Engineers, has received the NSF Director's Award for Collaborative Integration, the Ralph R. Teetor Educational Award and the Milton C. Shaw Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers, and was a Lilly Teaching Fellow at the University of Massachusetts Amherst.

Dr. Barry Horowitz,
Munster Professor of Systems and Information Engineering and Chair, University of Virginia

Dr. Horowitz is the director for the UVa research site of the National Science Foundation sponsored Industry/University Cooperative Research Center called WICAT (Wireless Internet Center for Advanced Technology). Prior to UVa, he was president and CEO of the MITRE Corporation. He received the Air Force's highest award for a civilian, is a member of the National Academy of Engineering, Tau Beta Pi and Eta Kappa Nu honor societies, and was awarded the AFCEA Gold Medal of Engineering in 1990. Dr. Horowitz is currently serving as a member of the Naval Studies Board (NSB) of the National Academy of Science, and has participated as a panel member on a variety of studies conducted by the Defense Science Board, the Army Science Board and the National Academy of Engineering.

Dr. William Rouse,
Professor and Executive Director of the Tennenbaum Institute for Enterprise Transformation, Georgia Institute of Technology

Dr. Rouse has over 30 years of experience in research, education, management, marketing, and engineering related to individual and organizational performance, decision support systems, and information systems. His expertise includes individual and organizational decision making and problem solving, as well as design of organizations and information systems. He has served as chair of the Committee on Human Factors of the National Research Council and as a member of the U.S. Air Force Scientific Advisory Board. Rouse is a member of the National Academy of Engineering, as well as a fellow of four professional societies —IEEE, INCOSE, IORMS, and HFES. He has received the Joseph Wohl Outstanding Career Award and the Norbert Wiener Award from the IEEE Systems, Man, and Cybernetics Society; a Centennial Medal and a Third Millennium Medal from IEEE; and the O. Hugo Schuck Award from the American Automation Control Council.



Dr. Jon Wade, *Associate Dean for Research, School of Systems and Enterprises, Stevens Institute of Technology*

Dr. Wade is a distinguished service professor in the School of Systems and Enterprises, and serves as the president and founder of AgilePower Systems, Inc. where he performs research in the development of hybrid solar power technologies. Wade was the executive vice president of engineering at International Game Technology (IGT). Before joining IGT, Wade spent 10 years at Sun Microsystems, during which time he managed the development of the UltraSPARC V based Enterprise Server family and served as the product manager for high-performance interconnects. Prior to this, he led new system development at Thinking Machines Corporation. In addition to his publications, Wade has received 11 patents in the areas of integrated circuits, computer architecture, networked systems and internal combustion engines.

Dr. Michael Griffin,
Eminent scholar and Professor of Mechanical and Aerospace Engineering, The University of Alabama in Huntsville

Dr. Griffin is one of the world's leading aerospace engineers and the 11th NASA Administrator. Dr. Griffin served as chief engineer and as associate administrator for exploration at NASA, and as deputy for technology at the Strategic Defense Initiative Organization. He is the lead author of more than two dozen technical papers, as well as the textbook, "Space Vehicle Design."
A registered professional engineer in Maryland and California, Griffin is an honorary fellow of the American Institute of Aeronautics and Astronautics (AIAA), a fellow of the American Astronautical Society, and a Senior Member of the Institute of Electrical and Electronic Engineers. He is a recipient of the NASA Exceptional Achievement Medal, the AIAA Space Systems Medal, and the Department of Defense Distinguished Public Service Medal—the highest award given to a non-government employee.

Research Commentary

How Do We Fix Systems Engineering?

The following are excerpts from Dr. Griffin's address to the Annual SERC Research Review on November 12, 2010.

In 2007-2008, NASA released its latest version of its Systems Engineering Manual. I looked at the document the Chief Engineer gave me and said, "This thing makes me want to throw up - it's all about what the rules are for systems engineering and what the process is and it doesn't have anything to do with how it's really practiced. The only job I was ever good at was being a spacecraft system engineer. Everything that I ever worked on that really flew worked, and we didn't do any of this stuff." The Chief laughingly agreed. So here we were, the Chief Engineer and the Administrator of NASA, the two highest authorities that had anything to say about the release of this document, both agreeing it didn't have anything to do with what we really did when we did engineering.

We knew we had to fix it. After several years of research, I have codified my views on where I think we've gone wrong.

Process versus practice

A major wrong turn is that we've addressed one of the two important aspects of systems engineering almost to the exclusion of the other.

I'm a pilot and have updated my own plane a number of times. Each time I also needed to update the plane's checklists for the critical flight activities. This checklist becomes the process I use to operate this complicated aircraft. It does not, however, have anything to do with the ability to actually fly the plane—you must already know how to fly and then fly in a way consistent with the checklist.

Just like checklists, a good systems engineering process you trust is critical to success. We teach great checklists - we've been refining them for 40 or 50 years. But in my view, we are not teaching students how to do systems engineering. We're training cooks or accountants and we need to train chefs and CFOs.

The purpose of systems engineering is to produce elegant designs

In the world of engineering design and real-world engineering, one hears the term "elegant design" all the time. A DC-3 is an elegant airplane design and the Ford Tri-motor is not. Why? I have tried, in all humility, to define what I mean by elegant design. I believe it to have at least four attributes, none of which by themselves have been defined either.

First, and most trivial, the design should work – that is, produce the intended result when operated.

There is no such theory of systems engineering. We know how to identify good systems engineers. We don't know how to identify good systems engineering. There are no theoretical criteria.

Second, it must be robust. Most of us have a feel for what's robust and what's not. The Russian Soyuz is robust, the space shuttle is not. The shuttle does things that are the stuff of science fiction—but everything has to be exactly right or it can be a really bad day. We don't have even the notion of a mathematical equation to measure the robustness of a design.

Third, the design must be efficient. I'm not talking just about something like thermodynamic efficiency, but more broadly. In linguistics, there is the concept of an efficient language; a large number of symbolic thoughts can be contained within very few symbols. English is a relatively efficient language. As a professional linguist told me one time, "English is the language which can be best understood when spoken badly."

Finally, an elegant design must produce few and minor unintended consequences. When have you ever sat in a design review as a professional engineer and heard the question "What does it do that you don't like?"

These aspects, then, are some of the unasked questions of systems engineering. I view them as part of a research agenda for the future of systems engineering and an educational agenda for those of us in the education business.

No theory of systems engineering

One reason we don't answer these questions is that today, we do not have a theory of systems engineering. We know how to identify good systems engineers. We don't know how to identify good systems engineering. There are no theoretical criteria.

Why no theory? I think I know one reason. We have to take into our tent disciplines that we have not previously included as being an essential part of engineering development. Intuitively we recognize that a theory of systems engineering will inherently involve soft and fuzzy subjects like cognitive science, decision theory, game theory and economics—non-engineering things. Engineers exist to turn ambiguity into certainty, and the ambiguity associated with those fields makes us uncomfortable.

If we're going to take the next step in our profession of engineering writ large, these are the things I think we need to do in academia and the world of professional practice. We have to develop a theory of systems engineering and our research must answer those critical questions of elegance that we simply cannot answer today.

***Michael Griffin**,*
Professor, University of Alabama in Huntsville

2010 SERC Research Projects

Graphical CONOPS Development Environment for Agile SE

Concepts of Operation (CONOPS) are critical artifacts in systems engineering. Although system stakeholder needs evolve rapidly as the operational and technological environment changes, the current international standards specify CONOPS documents that contain static text and graphics, rarely address human roles, and are hard to change and difficult to visualize. This research addresses the possibility of quickly and graphically articulating a CONOPS for new systems, missions, business processes, or feature sets. To identify potential solutions across a set of diverse stakeholders requires sharing both a mental model of the mission and an understanding of the environment. The team has begun referring to CONOPS development as concept engineering.

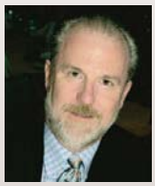
The research set out to develop an initial set of reusable primitives (core terms) organized into a hierarchy (taxonomy) that enable creating scenarios for different domains. A well-tested scenario was decomposed, and then a cognitive task analysis performed to determine what was necessary to plan and perform the actual scenario. A number of insights discovered in this process advanced the research to the next step—investigating a new scenario based on a news agency.

Current international standards specify CONOPS documents that contain static text and graphics, rarely address human roles, and are hard to change and difficult to visualize.

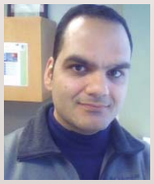
From these experiments, a rich taxonomy emerged that can be the basis for working with new domains. As an example, consider that transporting objects between locations, information gathering, and communications are all core to many actions. When looking at a military mission of close air support, objects are moving from one location to another, at specific times, and there is a high degree of communication and collaboration necessary. The same can be said for emergency response for an oil spill. While the objects may be domain-specific, movement, communications, and collaborations are common abstract actions. If those actions can be collected and represented graphically, then new scenario definitions can be accelerated and easier to understand.

A simplified architecture was developed, consisting of a highly collaborative user interface, the capability to create scenarios and CONOPS, a repository for reusable elements for use in new scenarios, the ability to add to, or extend the primitives, and an execution engine to put the scenarios in motion. A capability to interface with other systems/tools to exchange data was also deemed necessary.

Many current technologies were examined for their appropriateness for concept engineering. There are a number of human centered design philosophies, graphical programming techniques, and 3D (virtual) approaches that can be adapted to a concept engineering system (CES). The results of this work are being carried on in follow-on research moving toward a proof-of-concept prototype. The final report for this phase of the research is available on the SERC website as SERC-2010-TR-007.



Robert Cloutier
Stevens, PI



*and **Ali Mostashari***
Stevens, Co-PI

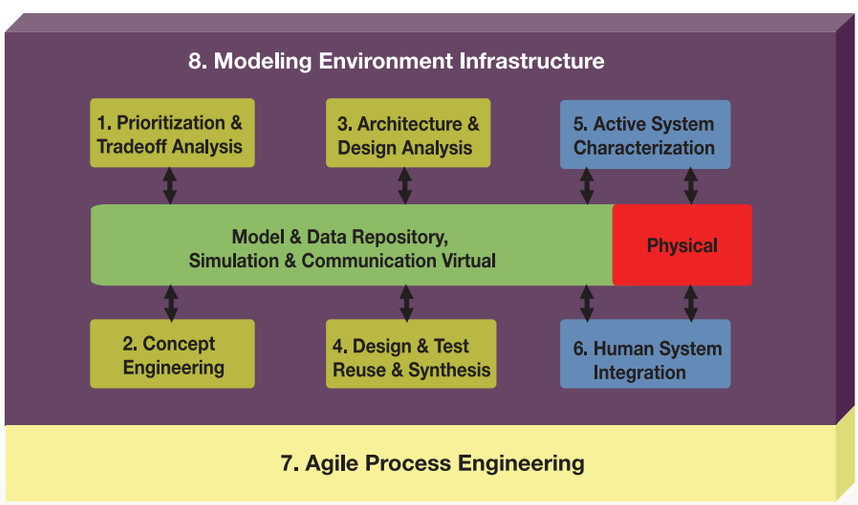
Research Activities

Systems Engineering Transformation

Traditional Systems Engineering (SE) is not adequate to meet the challenges of today's net-centric, information-based environments threatening SE with a loss of relevancy. Requiring elaborate documentation, detailed requirements definition, and static long term plans are all ineffective in these environments and counter-intuitive to the technologists working in this domain.
A number of trends collectively accelerate this challenge. Growing system complexity and criticality raise vulnerability. The ascendancy of software as the preferred solution continues in the face of significant gaps in our ability to understand, validate, and manage large evolving software ecosystems. The increasing speed of technological change, the rapid evolution of threats, and the decreasing schedules for development all lead to the sense that time itself is compressing. New systems envisioned by the defense and intelligence communities reflect, embrace, and reinforce these trends.

The team first formed a vision of a transformed Systems Engineering ability that consistently enables rapid, efficient delivery of continuously evolving capabilities while staying ahead of increasingly complex mission requirements and advancing technology capabilities. SE is a seamless part of system conception, development, and sustainment through flexible, integrated infrastructure (methods, processes and tools) that is adapted to the specific needs of the environment. The size and number of text-based artifacts are minimized, consistency of system representations is assured, and effective low-overhead communication is ubiquitous. Systems engineers are able to focus on thought-based SE tasks rather than mechanics. The time between need recognition and fielded capability is acceptable to the stakeholders.

Next, the team reviewed the current state of art in Systems Engineering in a number of different domains ranging from aerospace/defense, the electronics industry, and software systems as well as the future directions noted by INCOSE, the META Project, and a number of other studies. This analysis, combined with the needs necessary to support the SE vision, resulted in the construction of a framework with eight specific areas of research focus. A workshop was held with the sponsor and a number of preeminent SE researchers; it confirmed the relevance of these research thrusts and provided the necessary input that resulted in their refinement and the creation of the overall framework, as shown below in the diagram.



The Systems Engineering Transformation (SET) research project was commissioned to address this challenge by creating an integrated, modular roadmap of the research focus areas that are necessary to support a transformation of the discipline. The research task was led by Dr. Jon Wade of Stevens and Dr. Azad Madni of the University of Southern California, teamed with Dr. Colin Neill of Pennsylvania State University and a number of researchers from these and other universities.

Key Characteristics of Transformed SE

- Seamlessly integrated into life cycle
- Adjustable to specific needs
- Makes best use of human agents
- Supports asynchronous development
- Automated wherever possible
- Integrated (no sneaker-net)
- Knowledge based, continually evolving
- Supports analysis and decision making with automated data mining of artifacts
- Focuses on the interfaces

SET Research Area Framework

Finally, a research roadmap was developed for each of the research focus areas noted above. The roadmap provides a modular, integrated and extensible framework for transforming system engineering. These research efforts are integrated, such that together they provide value that is greater than the sum of their parts, yet remain modular, such that each area can proceed and provide value independently. Taken separately, these research areas have the potential to significantly advance the state of the art of Systems Engineering. Taken together, they have the potential to transform Systems Engineering. The specific results of this research have been documented in a final report and are used as reference in the Systems 2020 program, the development of SERC Research Strategy, and for the INCOSE Vision 2020 update efforts.

Jon Wade
Stevens, PI

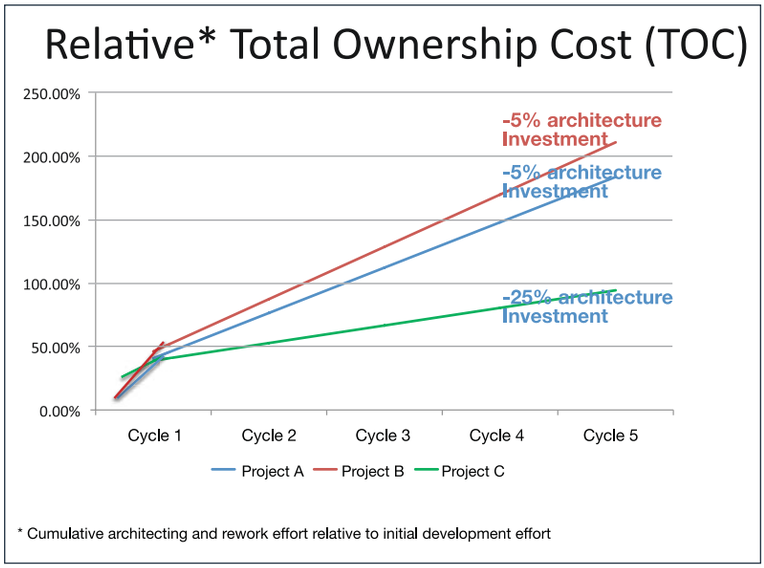
and ***Azad Madni***
USC, Co-PI

Valuing Flexibility

Flexibility is almost universally perceived as a good thing. Systems acquisition in the DoD is no exception, where programs typically strive to infuse some degree of flexibility into the system being developed. It is increasingly clear that future DoD systems need to be highly adaptive to rapid changes in adversary threats, emerging technology, and mission priorities, both during development and during operations. Traditionally, however, complex DoD systems have been designed to deliver optimal performance within a narrow set of initial requirements and operating conditions at the time of design. This usually results in the delivery of point-solution systems that fail to meet emergent requirements throughout their life cycles, that cannot easily adapt to new threats, that too rapidly become technologically obsolete, or that cannot provide quick responses to changes in mission and operating conditions. It is possible to design engineering systems with degrees of freedom such that they exhibit flexibility and/or robustness in future operating environments. However, unless a sound business case is required and can be made for the investment in flexibility, a program is likely to choose the point solution that minimizes the acquisition cost, and then to suffer the consequences.

A team of SERC researchers from Texas A&M University, Purdue University, University of Southern California, Air Force Institute of Technology, Naval Postgraduate School, and University of Virginia are collaborating on this project to identify, develop, and validate sound quantitative methods, processes, and tools (MPTs) to enable DoD leadership and program managers to make a convincing case for investments in system flexibility when acquisition decisions are made.

The team is exploring several methods of valuing flexibility, such as real options analysis, portfolio risk analysis, mission effectiveness analysis, cost-of-delay analysis, return on investment analysis, and total ownership cost analysis. The team is drawing on several sources of data to calibrate value-of-flexibility models, such as NPS' ship maintenance data, AFIT's modular munitions data, and USC's cost estimation model databases. It is also exploring tradeoff analyses between flexibility and other desired system properties. For example, system performance is often optimized by using tightly coupled architectures that are expensive to modify when changes are needed.



The figure shows example results from a total ownership cost (TOC) model calibrated to projects in the USC cost database. Projects A and B invested only 5% of their development costs in architecting for flexibility, and their resulting point-solution architectures were considerably more costly to modify. Project C invested 25% of its development costs in architecting for flexibility, and had much lower adaptation costs for comparable rates of mission and technology changes. These changes began during the later stages of the initial development cycle, so that Project C reached a TOC breakeven point by the end of Cycle 1. At this point, its TOC savings (and return on investment) were increasing significantly as the number of post-development change cycles increased.

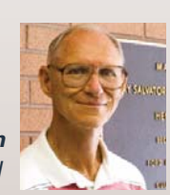
Such models can be used in acquisition situations to ensure that proposed projects have included at least one architecting-for-flexibility alternative in their analysis of alternatives, and have used a TOC analysis to determine their degree of investment in architecting for flexibility.

Quantitative models for the other approaches for valuing flexibility are being developed and calibrated. A review of the state-of-the-art showed that there is little unifying theory or guidance on best approaches to measure flexibility, quantify the value of flexibility in a prospective systems acquisition, or determine which approaches work best in which situations.

Considering this major gap in the state-of-the-art, a primary focus of the research activities continues to be on developing a coherent value-based definition of flexibility based on an analytical framework that is mathematically consistent, domain independent, and applicable under varying information levels. The team also conducted a critical evaluation of the theoretical foundations underlying current approaches, the dimensions of flexibility, measures of flexibility, value functions, and methods for incorporating flexibility – both at the design phase and the operational phase, to identify strengths and weaknesses of each approach. Candidate follow-on research includes addressing the issue of how to achieve flexibility in systems, including specific design principles that can be used to instill flexibility into the system design, and quantitative relationships between flexibility and other key system properties, such as safety, security, and mission effectiveness.

Abhi Deshmukh
Purdue, PI

and ***Barry Boehm***
USC, Co-PI



Research Activities

SE Capstone: A Pilot Study of 14 Universities to Explore Systems Engineering Learning and Career Interest through Department of Defense Problems

Increasing the systems engineering (SE) workforce continues to be a critical priority of the defense industry. In July 2010, the National Defense Industrial Association (NDIA) stated the quantity and quality of SE expertise is insufficient to meet the demands of the government and defense industry and outlined certain recommendations to build SE expertise and capacity. A 45% growth is expected in SE jobs in the next decade and numerous studies and workshops have highlighted SE workforce shortfalls in both number and capability. This research project is studying the impacts of novel Systems Engineering Capstone Experiences on learning and interest in pursuing careers in SE. Sponsored by the Department of Defense (DoD) Director, Defense Research and Engineering and the DoD's chief technology office, the strategic goal of this research is the development of SE talent to meet future DoD and defense industry needs.

SERC researcher Beth McGrath receives a Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring as Director of the Center for Innovation in Engineering and Science Education at Stevens (Official White House Photo by Pete Souza).

The basis for the research is a set of 14 STEM-related undergraduate and graduate "capstone" courses. In most cases, these are integrative, project-based courses involving teams of students working together to develop a product or prototype addressing an actual defense need. Eight civilian and six military universities are piloting methods, materials, and approaches to create new courses or enhance existing undergraduate and graduate courses that embed, infuse, and augment systems engineering knowledge (as defined in defense career fields) among students. Participating university faculty developed new course materials and other methods and strategies to provide substantive SE learning experiences and increase exposure to authentic DoD problems, such as low-cost, low-power computing devices, expeditionary assistance kits, expeditionary housing systems, and immersive training technologies. The hypothesis is that these experiences will increase awareness and interest in DoD problems and careers.

The results will inform the development of a national effort to substantially expand the number of universities with SE programs and improve the capabilities of systems engineering graduates. The pilot courses should lead to exemplary course materials, assessment instruments, and lessons learned, the adoption of which should accelerate the national effort.

The research will produce the following deliverables:

1. Principal investigators' (of the piloting universities) analyses of learning outcomes (student learning of SE concepts and skills, SE career interest, and interest in DoD and related careers and problems) based on progress as of January 2011 and June 2011

2. The research team's compilation, synthesis, and analysis of learning outcomes across the pilot programs for project periods through January 2011 and June 2011

3. Recommendations based on the pilot programs that will inform the development of a larger scale-up effort to build capacity for SE learning nationwide

"Our first semester...was a great success! We sponsored four projects, one within each of the Prepositioned Expeditionary Assistance Kit capability areas...Each of the teams produced a functioning prototype that met or exceeded the objectives established at the beginning of the semester. "

COL Nancy Grandy,
DDR&E/Rapid Fielding Directorate
Mentor to Penn State University, Capstone Team

Elisabeth McGrath
Stevens, PI

[1]*Rosato, D., Braverman, B., & Jeffries, A. (2009, November). The 50 best jobs in America. Money, 88-96.*

Systems Engineering Technical Leadership Development for the Defense Acquisition University (DAU)

The DoD has tremendous challenges in sustaining and growing its science, technology, engineering, and mathematics (STEM) workforces in support of acquisition excellence. The 2006 DoD Civilian Human Capital Strategic Plan codified the response to those challenges with the goal of developing "a civilian workforce that possesses the leadership, competencies, and commitment necessary for successful mission accomplishment." This research focuses on developing ways the DoD can leverage education to develop competencies required of technical leaders. As such, this task (RT4) is aimed at developing systems engineering leadership in practicing professionals. This is complementary to the objectives of RT19, "Research on Building Education and Workforce Capacity in Systems Engineering," which are to understand the methods through which SE learning and career interest may be optimized among undergraduate and graduate engineering students.

In 2009, the Defense Acquisition University (DAU) contracted with the SERC to research whether coursework is an appropriate way to train Department of Defense professionals in systems engineering (SE) technical leadership and, if so, to develop materials that would support a technical leadership curriculum. This included thoroughly researching the state-of-the-art and best practices associated with technical leadership training and education, and incorporating these best practices, along with SERC collaborator experience, into a trial technical leadership program (TLP) focused on systems engineering. The trial program constituted beta testing to support the development of final recommendations on the use of classroom training for SE technical leadership. The DAU provided additional guidance to determine how technical leadership fit into the DoD Systems Planning, Research, Development, and Engineering (SPRDE) career track, and how beta materials would be incorporated into the SPRDE curriculum.

Initial efforts focused on developing an appropriate framework for SE technical leadership competency. Competency topics and elements were collected from a wide variety of sources, including NASA, Nokia, BAE Systems, the DoD, and the Australian government, to develop an initial competency model. From these competency models, possible competencies for SPRDE Level IV were identified.

During the summer of 2010, the team developed and recommended a topical architecture as a framework for SE Technical Leadership Development curriculum and content development. This framework is comprised of three topical lenses:

Systems, Business and Teaming, and Enterprise and Strategy, each with underpinnings of communications, mentoring, ethics, and technical integrity as learning threads. The architecture provides for an expanding technical leadership perspective from tactical, near-term systems engineering, to the dynamics of business and teaming, to the broad, far-term perspective of enterprises and strategy. Subsequent research, supported by two collaborative Content Development Workshops and an Executive Forum of government and industry technical leaders, refined the topical architecture with the development of lens descriptions, desired learning outcomes, and summary focus areas of study for each lens.

The resulting description of the SE TLP development curriculum has taken shape as a multi-disciplinary, case based interactive course of study to prepare system engineers and technologists for leadership roles such as Chief Engineer, Technical Director, and Senior Technical Executive. Learning outcomes were established for each lens and used to guide the identification of summary focus areas within each lens. These focus areas will then serve as metrics to assess alignment and deficiency of existing courseware and support future content development of lectures, case studies, and other learning activities.

The 2010 research efforts also identified three other key pedagogical considerations: Mentoring, Learning Thread Integration, and development of a Multi-mode Case Based Learning Framework. The Case Based Learning Framework will provide guidance for developing classroom simulations of real world technical leadership experiences and events that reflect the SE contextual challenges of ambiguity, complexity, and change. Together these characterize the most adverse environment in which technical leaders must perform. Ultimately, this is also the environment where RT4 findings will be put to test by graduates of the curriculum.

Future research objectives include support in the development and delivery of a series of pilot Systems, Business and Team, and Enterprise and Strategy courses to DAU selected students. Student, lecturer, and student feedback resulting from the pilots will be treated as beta test data for further refinement of a recommended SE Technical Leadership Development program for the DAU.

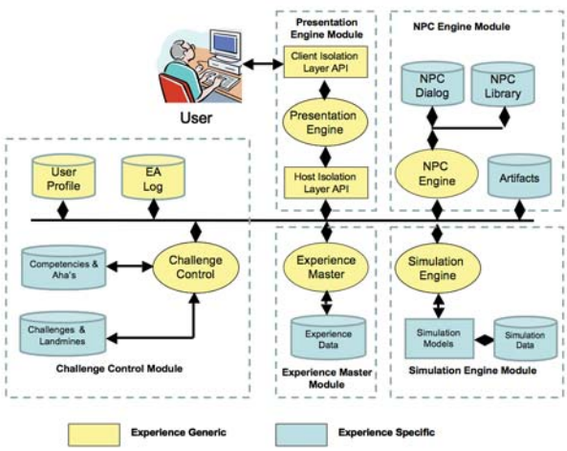
Valentin Gavito
Stevens, PI

Developing Systems Engineering Experience Accelerator Prototype and Roadmap

The overly long maturation period for new systems engineers due the length of projects and learning opportunities, coupled with today's learners' preferences for interactive, experiential, and problem-based learning environments, highlight that traditional systems engineering education is not adequate to meet modern systems and societal demands.

The Experience Accelerator (EA) project seeks to transform the education of systems engineers by creating a new paradigm capable of significantly reducing the time to mature a senior systems engineer while providing the skills necessary to address emerging systems challenges.

Experience Accelerator Block Diagram



The research hypothesis is that by leveraging simulation technology to create an experiential, emotional state coupled with reflective learning, the EA will effectively compress time and greatly accelerate the learning and maturation process of a systems engineer. Targeted outcomes include moving systems engineers to the next level of proficiency in one or more SE competencies and increasing their ability to apply these skills effectively on the job. The role targeted for improvement is the Executive Level DoD Lead Program Systems Engineer. An additional goal is to utilize an open architecture so that the EA can serve as a framework and toolkit for future training applications across a variety of contexts.

During this first year, the EA project established project goals and success metrics, identified critical competencies and maturation points, defined the supported learning process, and selected technologies with an open architecture in mind. The team is currently developing the initial prototype for demonstration.

Several target modes for the EA were identified, including a single-user mode that will be the focus of the first year prototype, a single-team multi-user mode, allowing for a team of users to work as a team in the environment, and a multi-team mode, supporting multiple teams competing in the environment.

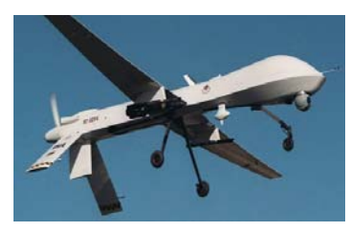
Targeted competencies were specified that would include technical expertise, including technical and analytical skills, technical leadership skills, and technical management skills. The EA will also target domain independent competencies, including project management and broad professional competencies. Through a learning process incorporating a concrete experience, reflective observation, abstract conceptualization, and active experimentation, users will accelerate their SE competency development.

Through user history and a competency survey, EA will structure an individualized "experience" within the simulation. This will target specific competencies and incorporate targeted "Aha moments," learning outcomes and heuristics that will advance the learner's competencies and skills through allowing the user to fail safely. The user profile will track a behavioral component composed of user experiences and user-specific competencies, as well as an attitudes component determined through a social cognitions inventory, and a personality and values component, determined through personal styles and value alignment inventories.

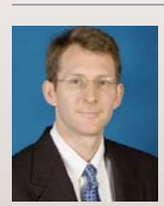
The high-level architecture for the EA includes a challenge control module, simulation engine module, presentation engine module, non-player character (NPC) engine module, and experience master module. The challenge control contains user profiles and EA experience history logs, and uses the competency taxonomy and "Aha moments" to determine appropriate challenges and landmines. The simulation engine determines the future state of the system and outputs to be presented to the user. The presentation engine module will accept inputs from the user and provides the presentation of the experience interface. The NPC engine module represents NPCs in the simulation and creates and assembles the content for user interactions. Finally, the experience master module controls the other modules ensuring proper sequencing, state variable control and logging.

A review was conducted of available open source and commercial technologies. A suite of primarily open source technologies was chosen to allow the project to leverage another project that has successfully prototyped 2D and 3D virtual environments capable of running on DAU computers.

The single user experience for the first-year EA prototype will be a scenario where the user is a Program Systems Engineer (PSE) on an unmanned aerial vehicle (UAV) acquisition program. The program has run into problems in the integration phase, and the user is replacing the past PSE on the project. The user must diagnose existing problems and determine how to correct them in order to make the project a success while staying on schedule and budget.



Researchers from Purdue University, Stevens Institute of Technology, Georgia Tech University, and the University of Southern California are completing the design and development of the first year prototype.



Jon Wade
Stevens, PI

and ***Bill Watson***
Purdue, Co-PI

Expanding Portfolio and Outreach

Art Pyster, *Deputy Executive Director*

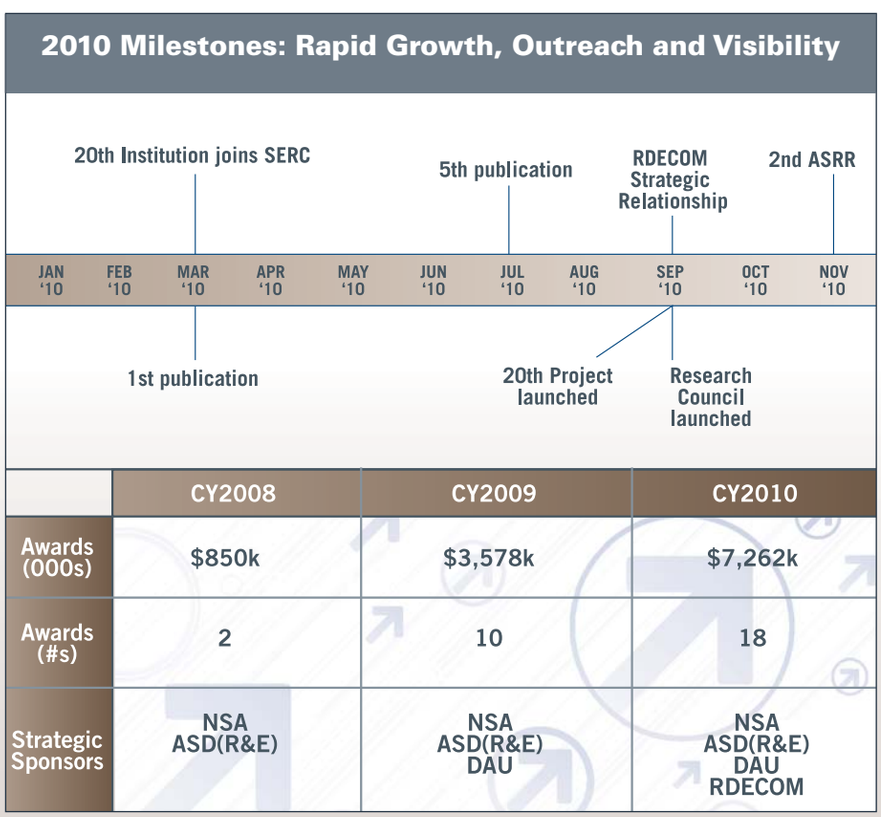
SERC has experienced rapid growth, greater diversity in research sponsors, and enhanced visibility in 2010. Awards to the SERC rose from $3.6M in 2009 to $7.3M in 2010. In September 2010, we launched our 20th research project and formed the Research Council, described on page 5, to help manage that expanding research portfolio. The Army's Research Development and Engineering Command (RDECOM) became a new strategic sponsor. The 2010 Annual SERC Research Review, held on November 9-10 at the University of Maryland, attracted more than 110 participants from government and industry to discuss the SERC research program. The number of researchers participating in all research projects increased to 165, and we are approaching a critical mass of research projects in some areas, particularly human capital development.

As our research portfolio and sponsors grow and diversify, our governance model for the SERC must evolve to keep pace. Since its inception, the terms SERC and SER-UARC have been synonymous, but that is changing. The SERC is now a center that operates the SER-UARC as its most important element – its anchor – built around the concept of a multi-collaborator virtual research organization. That concept has proven effective in rapidly responding to sponsor needs while developing the underlying research foundations needed to advance the state of the art. In fact, that concept has been so successful that we are "cloning" it to support sponsors outside the DoD, creating an even larger pool of SE research to tackle the hard problems that plague DoD and everyone who is building large complex systems. The first example of this is a new contract being managed by the SERC to collaboratively perform SE research for the U.S. Federal Aviation Administration. That research, expected to be on such topics as safely and securely integrating new capabilities into an extremely large and complex operational system of systems, will tangibly benefit DoD.

Sponsors	2010 ($K) Awards
NSA	$1,025
ASD(R&E)	$4,574
DAU	$800
Air Force	$153
Army	$910
TOTAL	**$7,262**

Milestones

Doris Schultz, *Director of Operations*



	CY2008	CY2009	CY2010
Awards (000s)	$850k	$3,578k	$7,262k
Awards (#s)	2	10	18
Strategic Sponsors	NSA ASD(R&E)	NSA ASD(R&E) DAU	NSA ASD(R&E) DAU RDECOM

SERC Advisory Board

The SERC Advisory Board is a select group of distinguished leaders with extensive experience in senior levels of government and the management of research organizations. Chaired by the Honorable Michael Wynne, the Board advises the SERC executive team on strategy and reviews SERC plans and progress.

The Honorable Michael Wynne, Chair Mr. Wynne currently serves as a senior advisor to the President of The Stevens Institute, and the Chair of the Advisory Board for the Systems Engineering Research Center. He was the 21st Secretary of the Air Force, and before that the Undersecretary for Acquisition, Technology and Logistics in the office of the Secretary of Defense, both spanning 2001 to 2008. He served in the Air Force for seven years, finishing as assistant professor of Astronautics at the Air Force Academy. He spent three years with Lockheed Martin Corp as the general manager for Space Launch, and 23 years with General Dynamics working in aircraft, armored vehicles, and the space division. He retired as senior vice president from General Dynamics.

Marion Blakey Marion C. Blakey is president and chief executive officer of the Aerospace Industries Association. AIA represents the nation's leading manufacturers and suppliers of civil, military, and business aircraft, helicopters, unmanned aerial vehicles, space systems, aircraft engines, missiles, materiel and related components, equipment services and information technology. Ms. Blakey became the eighth full-time chief executive of the association in 2007. Before that, she served a five-year term as administrator of the Federal Aviation Administration. Prior to being named FAA Administrator, Blakey served as chairman of the National Transportation Safety Board. Blakey served as administrator of the National Highway Traffic Safety Administration, and held key positions at the Department of Commerce, the Department of Education, the National Endowment for the Humanities, the White House, and the Department of Transportation.

Dr. Ruth David Dr. David is president and CEO of Analytic Services Inc. Prior to ANSER, she was Deputy Director for Science and Technology at the Central Intelligence Agency and was awarded the CIA's Distinguished Intelligence Medal, the CIA Director's Award, the Director of NSA Distinguished Service Medal, the NRO's Award for Distinguished Service, and the Defense Intelligence Director's Award. Dr. David is a senior fellow of the Defense Science Board, a member of the Department of Homeland Security Advisory Council, the National Security Agency Advisory Board, the Corporation for the Charles Stark Draper Laboratory, Inc., and the Hertz Foundation Board. She was elected into the National Academy of Engineering in 2002 and currently serves as a councilor of the NAE, chairs the National Research Council (NRC) Board on Global Science and Technology, chairs the NRC Standing Committee on Technology Insight–Gauge, Evaluate, and Review (TIGER), and is a member of the Standing Committee on Science, Engineering, and Public Policy (COSEPUP).

Alfred Grasso Mr. Alfred Grasso is president and chief executive officer of The MITRE Corporation. He is responsible for developing and leading the corporation's overall strategic and business operations and cultivating key sponsor and customer partnerships. Mr. Grasso is also a member of MITRE's Board of Trustees. Mr. Grasso is a member of the Defense Science Board, vice chair of the Armed Forces Communications and Electronics Association (AFCEA) International Board of Directors. He is a special advisor to the STRATCOM CYBER Strategic Advisory Group. Mr. Grasso is the president of the Board of Directors of the National GEM Consortium, a nonprofit that works to promote the participation of under-represented groups in science, technology, engineering, and mathematics (STEM) careers.

Dr. Michael Griffin Michael Griffin, one of the world's leading aerospace engineers and the 11th NASA Administrator, is currently an eminent scholar and a professor of mechanical and aerospace engineering with The University of Alabama in Huntsville. Dr. Griffin served as chief engineer and as associate administrator for exploration at NASA, and as deputy for technology at the Strategic Defense Initiative Organization. He is the lead author of more than two dozen technical papers, as well as the textbook, "Space Vehicle Design." A registered professional engineer in Maryland and California, Griffin is an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA), a Fellow of the American Astronautical Society, and a Senior Member of the Institute of Electrical and Electronic Engineers. He is a recipient of the NASA Exceptional Achievement Medal, the AIAA Space Systems Medal, and the Department of Defense Distinguished Public Service Medal, the highest award given to a non-government employee.

John G. Grimes Mr. Grimes served as the Assistant Secretary of Defense for Networks and Information Integration / Department of Defense Chief Information Officer from 2005 until 2009. Prior to that, he served on the White House National Security Council Staff as Director for National Security Telecommunications Policy; Director of Defense Command, Control and Communications Programs; and Senior Director White House Situation Support Staff. Mr. Grimes has served as Deputy Assistant Secretary of Defense for Defense-wide Command, Control and Communications and was the Deputy Assistant Secretary of Defense for Counterintelligence and Security Countermeasures. He is the recipient of the AIAA Command, Control, Communications and Intelligence Award, the 2010 AFCEA SARNOFF Award, and two U.S. Presidential Rank awards.

SERC Leadership

- **Executive Director:**
  Dr. Dinesh Verma
  Dean and Professor, School of Systems and Enterprises, Stevens Institute of Technology

- **Deputy Executive Director:**
  Dr. Arthur Pyster
  Distinguished Research Professor, School of Systems and Enterprises, Stevens Institute of Technology

- **Director of Research:**
  Dr. Barry Boehm
  Director Emeritus of the USC Center for Systems and Software Engineering, and TRW Professor of Computer Science at the University of Southern California

- **Director of Operations:**
  Ms. Doris Schultz
  Stevens Institute of Technology

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For more information about the SERC,
please visit the SERC website at

www.sercuarc.org

The SERC Collaborators

University or Research Organization

1. Stevens Institute of Technology
2. University of Southern California
3. Air Force Institute of Technology
4. Auburn University, Auburn, AL
5. Carnegie Mellon University
6. Fraunhofer Center at University of Maryland
7. Georgia Institute of Technology
8. Purdue University
9. Missouri University of Science and Technology
10. Naval Postgraduate School
11. Pennsylvania State University
12. Southern Methodist University
13. Texas A&M
14. Texas Tech University
15. University of Alabama - Huntsville
16. University of California - San Diego
17. University of Maryland - College Park
18. University of Massachusetts Amherst
19. University of Virginia
20. Wayne State University