System of Systems

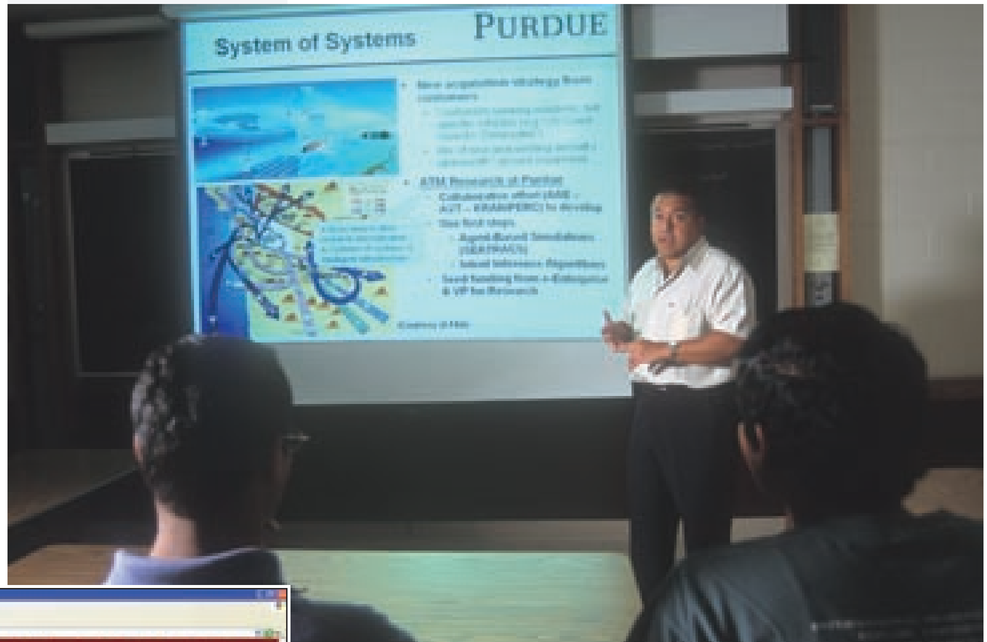
Connecting the seemingly different parts with the whole helps researchers approach large-scale problems in this signature area perched squarely on the cutting edge.

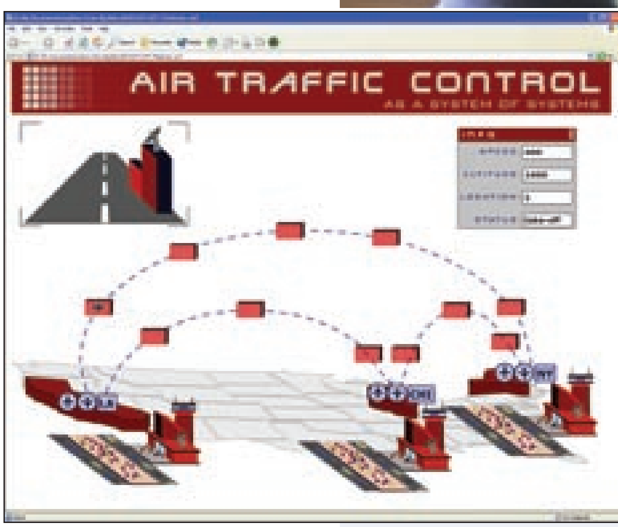
It's the enigmatic signature area that takes some explaining. To truly wrap your mind around System of Systems (SoS), you could begin by looking skyward and thinking of air travel. Or ask Thomas Farris, the head of aeronautics and astronautics and co-chair of the same-said signature area. Given his background, he's likely to point to the complicated skies, too.

Farris uses the airplane as an example of a large-scale, complex system. Many systems, he says, operate various parts of the plane, but the plane flies when all its systems work in tandem and doesn't fly if the systems work independently of each other.

An airport is another complex system; however, the airport involves aircraft, support trucks, baggage-handling equipment, and many other systems that can and do operate independently of each other. For the airport to function, it needs to have the right mix of these independent systems, and these systems need to cooperate with each other. Air traffic control is another example combining aircraft, control centers, airports, satellites, radars, and so on. All of travel—from the time you leave your home until you arrive at your destination—can be considered a system of systems as you use a car, a taxi, a shuttle bus, the airplane, etc.

This emerging system-of-systems concept describes the large-scale integration of many independent, self-contained systems in order to satisfy a global need. From air traffic control to constellations of satellites, these complex multi-systems





SoS/IIS Classrooms: Mario Rotea, a professor in aeronautics and astronautics, preaches system-of-systems thinking in his classroom. Also spreading the word are Rotea's colleagues, including Dominick Andrisani, a professor in aeronautics and astronautics, Alok Chaturvedi and Shailendra Mehta, professors of management, and Tom Carney and Michael Nolan, professors of aviation technology.

are very interdependent. In other words, each affects the other. The synthesis of these very large systems often results in different problems than those presented by the design of a single, but complex, system usually addressed by engineers. Examining how these individual systems can be brought together and coordinated as part of a bigger picture provides an exciting new area for research and discovery at Purdue that could have many applications across many disciplines.

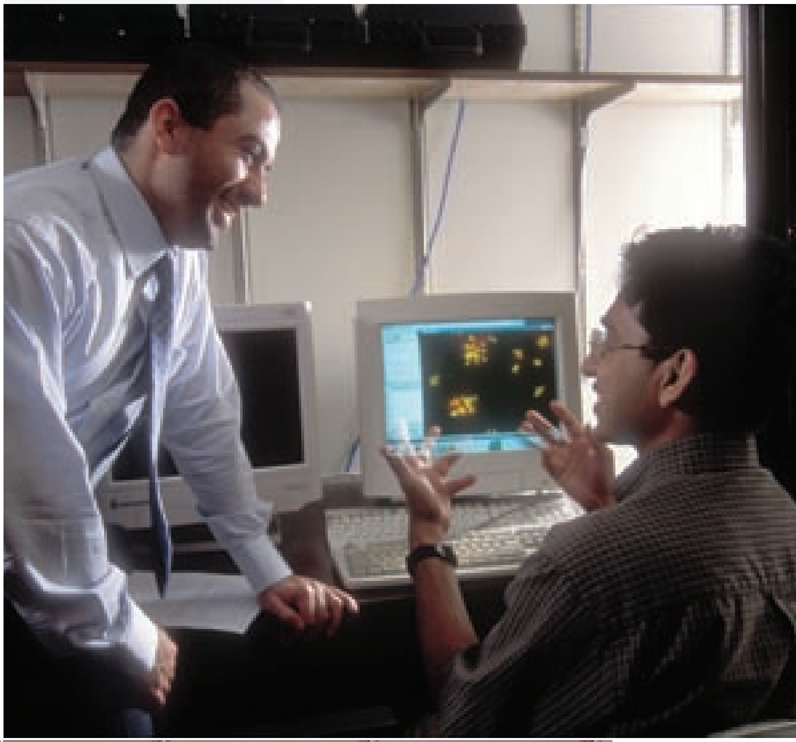
Mario Rotea, a professor in aeronautics and astronautics, is looking at the big picture of air traffic management. With an approach that combines SoS and Intelligent Infrastructure Systems, a Purdue team (see caption) will work at the interface between information technology, economics, prediction of complex dynamic behavior, and aviation technology to create an air traffic management system that ensures low cost, speedy, and safe transportation of humans and goods. They've come up with Synthetic Environment for Air Traffic Control Simulations (SEATRACS).

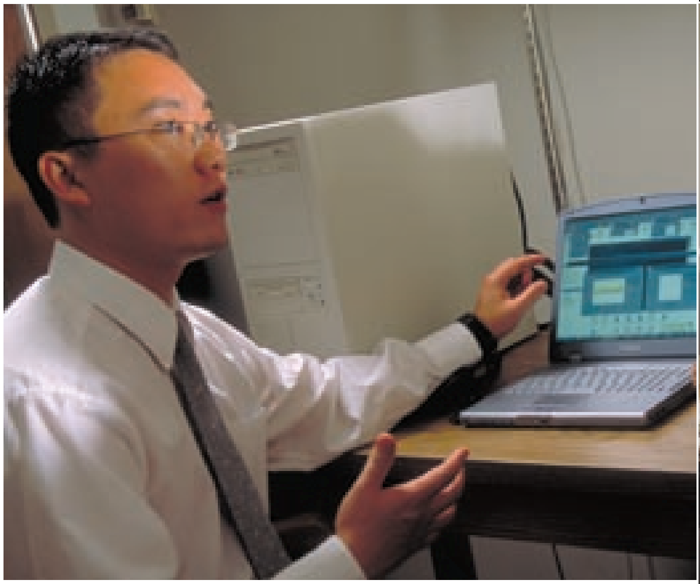
"SEATRACS will analyze and test decision policies with regard to air traffic flow within a specific segment of the air traffic management network," Rotea says. "We're developing new models and algorithms to determine aircraft intent in the presence of time-varying constraints such as those imposed by the need to avoid severe weather and neighboring aircraft."

Back on land, Srinivas Peeta, a professor in civil engineering, works with other gargantuan systems of a nation's infrastructure—transportation, water, energy, communication, and financial networks. "These are interdependent systems to various degrees," he says, "but are addressed in isolation, or by cursorily acknowledging the couplings in engineering practice.

"In the SoS context," Peeta continues, "we view the problem in terms of these systems representing coupled layers of a grand infrastructure network, more generally labeled a 'network of networks.' Among others, the SoS perspective has implications for analyzing the cascading effects associated with terrorist attacks or the summer 2003 power blackout in the northeast U.S. In turn, we can incorporate those insights into engineering designs."

SoS is inherently multidisciplinary. While specific problems will require specific expertise, the principle premise here is that





Network of Networks: Srinivas Peeta (right), a professor in civil engineering, works with graduate students, Weimin Zhou (left) and Alexander Paz and Kannan Viswanath (left and right above) to model different infrastructure systems as a multiple-layer system of networks that interact with one another.

common characteristics of all these large, complex problems can lead to general tools and methodologies to support them.

Research outside of the Schools of Engineering will draw in experts in game theory and uncertainty. Correspondingly, this new area will be beneficial to schools and departments across campus, including mathematics, economics, and management.

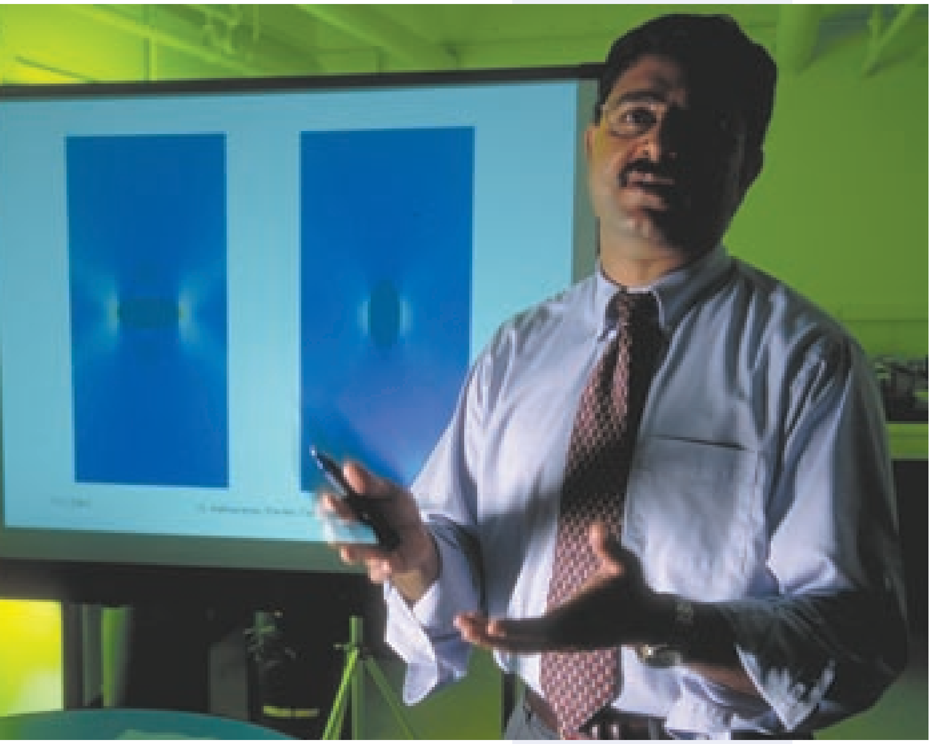
Farris knows SoS presents a real opportunity for Purdue's leadership. "We have a lot of world class leaders in their own capacities that will come together," he says. "We also have a lot of related talents and great industrial partners."

Projects can be as varied as imagining future combat systems for the Department of Defense, redesigning the port system in Boston, and reducing the costs of spy satellites. The cross-disciplinary work will address internet-related problems and large-scale construction projects like the "Big Dig" in Boston, as well as how to rebuild oil pipelines in Iraq, or simulate emergency responses to natural disasters or terrorist attacks.

The Boeing Corporation has expressed great interest in Purdue's SoS effort, and business strategists at Lockheed-Martin, Northrop-Grumman, Raytheon, and elsewhere are looking into this big-picture problem solving as well. There are also opportunities to affect supply chain management, public construction, and homeland security.

The opportunity for graduate students is also large. By bringing together a diverse group, techniques and methods lacking in some areas can be approached with new skills sets. Students will gain real-world experience running the gamut of cybernetics, control theory, object-oriented programming, chaos theory, artificial intelligence, mathematical genetics, evolutionary biology, economics, group dynamics, and sociology. While still being trained as engineers, they'll benefit from training that builds on the traditional foundation. Ultimately, this new way of thinking, this system of systems, will make these students highly desirable in the complex marketplace.

Shape Design Moment: Ganesh Subbarayan, an associate professor in mechanical engineering, takes complex systems and looks for ways to design them by piecing together their elements. In this particular study, he is trying to determine the optimal orientation of a hole in a plate that leads to the smallest stress.



Satellite Solutions Point the Way to System of Systems Design

Satellite Shoptalk: William Crossley, an associate professor in aeronautics and astronautics, confers with Rania Hassan, a Ph.D. student, about design optimization.

William Crossley knows the impossibility of scheduling innovation. Great ideas rarely conform to daily planners and Crossley, an associate professor in aeronautics and astronautics, says traditional engineering practices often focus on a "design by heroics."

"A common method," he says, "is for everyone to rally around someone's good idea to make it work. That's not a bad approach, but the tools and the formulations, and the way you set up the problem are unclear; especially when you are trying to design a complex system of systems (SoS) that combines many other complex, large-scale systems."

In a design optimization approach, engineers set up a framework of the problem and use formal techniques to find solutions. This way, researchers aren't relying on one person's great idea. Crossley hopes to extend optimization approaches to SoS problems.

Rania Hassan, a Ph.D. student in aeronautics and astronautics working with Crossley, is applying optimization to satellites. The motivation was to make space-borne telecommunication services more economically feasible and competitive with terrestrial-based services. Her thesis project involves design optimization under uncertainty of large-scale, complex systems.

Ensuring guaranteed space-borne services are one reason why satellites are so expensive. Reliability is paramount, so there are high levels of redundancy included in the design. Designers commonly apply deterministic margin-based approaches to allocate redundancy and estimate system reliability. Hassan wanted to include uncertainties involved in reliability estimation early enough in the process so designers could make a more-informed risk analysis.

"Performing design optimization under uncertainty for complex, large-scale systems is computationally costly," Hassan says. "The state-of-the-practice makes designers run codes for very long periods. That discourages engineers and that's why they use the deterministic methods, which result in over-sized, highly-redundant and expensive systems."

Hassan developed a method to reduce the time to do the calculations of design under uncertainty for large-scale systems. With Crossley, she explored using a genetic algorithm–a population-based search method that performs optimization-like tasks–to provide samples to evaluate the statistical characteristics of uncertain performance criteria. In the end, this time-saver could prove to be a great money-saver, and the approach provides one of the general methodologies for tackling SoS problems.