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AERO-ASTRO

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Cover: This Aero-Astro issue offers a look at the future of the Aero-Astro Department as 11 young faculty members describe their motivations and interests.

Dear colleagues and friends:

This issue of Aero-Astro is about the future of the MIT Aeronautics and Astronautics Department, told from the perspective of the people who, more than any others, will make it happen — our young faculty members. Told in their own words, these articles describe their motivations and interests.

The articles build on the mission, values, and strategic directions described in our recent report, "Aero-Astro: Our Future" (http://web.mit.edu/aeroastro/about/pdfs/stratrpt07.pdf), which identifies eight areas that represent grand challenges and grand opportunities for the department and for aerospace:

- space exploration
- autonomous, real-time, humans-in-the-loop systems
- aviation environment and energy
- aerospace communications and networks
- aerospace computation, design and simulation
- air transportation
- fielding of large-scale complex systems
- advancing engineering education

As you read through these pages we think you will agree that our future is in very good hands.

To learn more about any of these individuals, or the work of any of our department's faculty and staff, we welcome you to send an email, or visit us in Cambridge, MA.

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David L. Darmofal
David Darmofal
Associate Head

Department Head Ian Waitz (left) and
Associate Head David Darmofal

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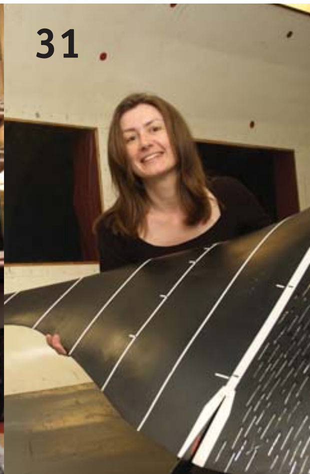


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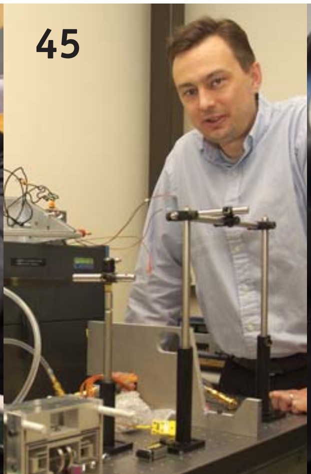
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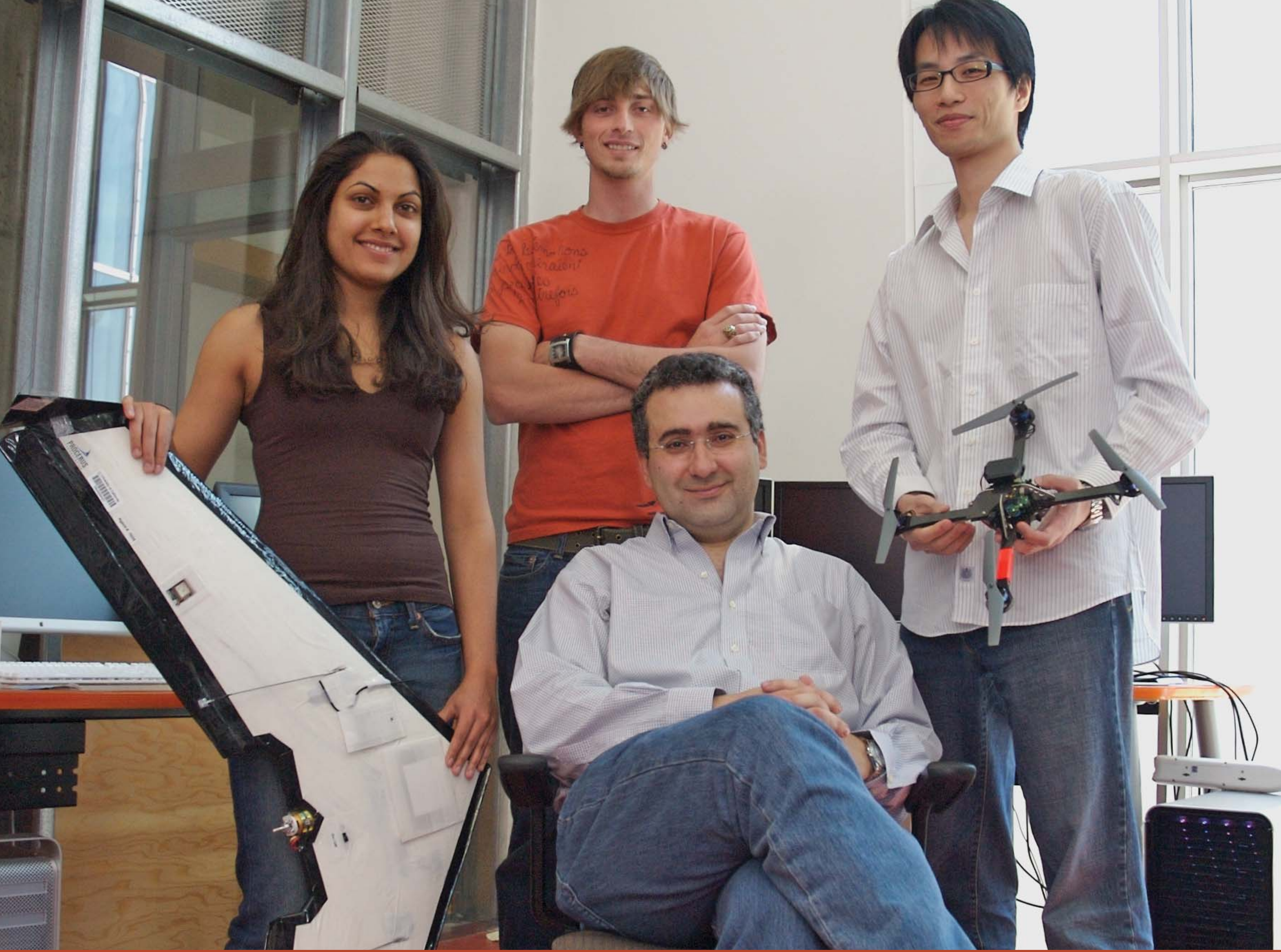


Emilio Frazzoli and his grad students (from left) Sameera Ponda, Joshua Bialkowski, and Byunghoon Kim in his lab with some of the vehicles they fly in their Aerial Robotics and Embedded Systems group. (William Litant/MIT photograph)

EXPLORATION, MONITORING, RESCUE ARE POTENTIALS FOR AUTONOMOUS VEHICLES

By Emilio Frazzoli

In little more than a year, the MIT team designed an extremely capable autonomous car, which was among only six of 89 competitors' vehicles to successfully complete the DARPA Urban Challenge.

Autonomous vehicles are a critical and rapidly developing technology both for civilian and military applications. Their use ranges from environmental monitoring and planetary exploration, to search and rescue operations, and national security. Autonomous and semi-autonomous aircraft are used extensively in military operations, and modern spacecraft exhibit ever-increasing capabilities for autonomous onboard decision-making.

The MIT Aeronautics and Astronautics Department plays an important role in the development of the state of the art in UAV control. As a doctoral student at MIT in 1997-2001, I helped develop an autonomous helicopter capable of performing acrobatic maneuvers, such as barrel rolls and split-S's. My Ph.D. work started when my advisor, Eric Feron, and I went to a model airplane flying field with a video camera, and taped expert pilots performing impressive acrobatic feats with their remotely controlled helicopters. We decided that we would teach a computer to perform similar acrobatic routines, and to exploit their maneuverability to fly aggressively in a dangerous environment, for example, to evade threats. To do so, I devised an approach based on "motion primitives," that is, a mathematical formalization of the intuitive concept of "maneuver."

Such motion primitives, chosen from a library stored in the flight computer's memory, could be combined online to construct complicated trajectories. Remarkably, this approach allowed us to rewrite the equations of motion for a complicated, high-performance vehicle

Autonomous systems have their applications for earth-bound, as well as aerial vehicles. Emilio Frazzoli worked alongside others to develop this vehicle for the 2008 Defense Advanced Research Project Agency robotic vehicle challenge. (Jason Dorfman photograph)

in a form that resembles a kinematic system (such as a robotic arm), thus simplifying dramatically the calculations required to plan and optimize flight trajectories. Moreover, the maneuvers in the library can be designed in such a way that they can be performed reliably, thus ensuring that the vehicle will remain safe even when executing challenging maneuvers.

TACKLING LIMITED INTERACTION ABILITY

Although the capabilities of modern autonomous vehicles are impressive, their ability to interact safely and efficiently with other vehicles (human-piloted or autonomous) is currently limited. The problem of designing vehicles that can play nice with others was at the core of last year's DARPA Urban Challenge, a competition for robotic vehicles sponsored by the U.S. Defense Advanced Research Project Agency. MIT was one of the 89 university and industry teams from around the world that competed. Unlike previous editions of the Challenge, the racecourse was no longer primarily dirt roads, but mostly paved roads, in a road network typical of suburban areas, featuring intersections, rotaries, and parking lots. There were also winding roads and high-speed stretches.

However, the major new feature of the Urban Challenge was the introduction of traffic. Autonomous robots were expected to abide by the traffic laws and rules of the road; in principle, the autonomous vehicles were expected to display the degree of proficiency in driving skills comparable to that required to get a California driver's license. For example, vehicles were expected to stay in the correct lane, maintain a safe speed, yield to other vehicles at intersections, pass vehicles when safe to do so, recognize blockages, execute u-turns, and park in an assigned space.

Together with Professor Jonathan How, I participated in the development of the planning and control system for the vehicle. Participation in this project was intense and rewarding. In little more than a year, the MIT team designed an extremely capable autonomous car, which was among the six vehicles that successfully completed the 60-mile race. In fact, with a fourth place finish, MIT was the first rookie in the final rankings, an achievement that made us proud. This achievement required an intense effort by all involved — undergraduate and graduate students, post-doctoral researchers, and faculty — culminating in a very emotional moment as the "start" command was sent by DARPA officials; an experience some compare to seeing a child leaving for college. At that point, we could no longer control the behavior of the car, we had to trust our prior efforts to teach the vehicle the best strategies to successfully handle the events in the race on its own.

Modern technological advances make the deployment of large groups of autonomous mobile agents with onboard computing and communication capabilities increasingly feasible and attractive. However, our understanding of such systems is still very limited. As a consequence, we are not yet close to realizing the potential offered by the ability to deploy a large number of UAVs able to perform complex missions.

WE ARE NOT YET CLOSE TO REALIZING THE POTENTIAL OFFERED BY THE ABILITY TO DEPLOY A LARGE NUMBER OF UAVS ABLE TO PERFORM COMPLEX MISSIONS.

Some of the limitations impeding a more widespread use of autonomous systems, both in terms of availability, and in terms of numbers of vehicles concurrently active in a shared environment, include:

- requiring large, dedicated, and well-trained ground control crews, as well as specialized equipment
- limited ability to cope with uncertainty in a complex and dynamic environment with limited information, including on board failures, unforeseen events, and adversarial actions
- poor understanding of the effects of scale on the complexity, performance, and cost of systems comprised of a large number of individual, (semi-)autonomous, or human-controlled units
- limited interoperability across different vehicle systems, including human-piloted vehicles

In my current work, I concentrate on these questions for a class of problems involving a large number of mobile agents, coordinating through a wireless communication network to achieve dynamic tasks defined over a geographically extended region. For example, agents can represent mobile sensors required to collect information about a time-varying spatial field (e.g., temperature profiles, chemical concentration), or mobile relays providing wireless communication services over a region. The main objective of my work is the design of scalable, robust, and adaptive algorithms with provable performance, and with a precise characterization of the implementation complexity (e.g., in terms of computational resources, cost, or communication network bandwidth). Furthermore, I am interested in examining how the performance and complexity characteristics of the system change as its dimension grows, both in terms of the number of agents, and of the number of tasks.

ENHANCING NETWORK SAFETY, EFFICIENCY

This research requires expertise in a variety of disciplines, from systems and control theory, to optimization algorithms, distributed computation, communication networks, and operations research. With a diverse group of students from a variety of academic backgrounds, I am pursuing several projects that will ultimately enhance the safety and efficiency of autonomous vehicle networks and their ability to interact with human-piloted vehicles. Ideally, one could conceive a Turing test for autonomous vehicles, in which a human observer tries to determine which one of two operating (e.g., maneuvering in traffic) vehicles is running autonomously and which is controlled by an expert pilot. Even though much remains to be done—for example, to improve the situational awareness of autonomous vehicles, their ability to interpret the wealth of sensory information, and especially to infer the intentions of others—our recent accomplishments demonstrate that the goal of designing an autonomous vehicle able to pass such test—thus being indistinguishable from a human-controlled vehicle—is, perhaps, closer than what we could have imagined just a few months ago.

Emilio Frazzoli is an Associate Professor in the MIT Aero-Astro Department. He received the Laurea degree in Aeronautical Engineering from the University of Rome "La Sapienza" (1994), and a Ph.D. in Navigation and Control Systems from MIT (2001). Previously, he was an officer in the Italian Navy, and a spacecraft dynamics specialist at Telespazio S.p.A, in Rome. His main research interests are in planning and control of autonomous vehicles, and mobile robotic networks. He may be reached at frazzoli@mit.edu.

Missy Cummings and doctoral student Sylvain Bruni with the Humans and Automation Lab's new Mobile Advanced Command and Control Station, a portable testbed for human supervisory control research. (William Litant/MIT photograph)

SUPERVISING AUTOMATION: HUMANS ON THE LOOP

By Mary “Missy” Cummings

The human link to the control mechanism becomes critical as systems grow larger, with increasing numbers of components and additional operators, such as in an air traffic control environment.

My primary research focus is the field of human supervisory control: intermittent human operator interaction with a remote, automated system in order to manage a controlled process or task environment. Human supervisory control represents humans “on-the-loop,” as opposed to “in-the-loop.” Example human supervisory control settings include air traffic control, process control, military and space command and control, crises response management, and unmanned vehicle operations. With the rapid expansion of automated technology in everyday settings, human supervisory control settings are expanding to medicine, driving, and business and commercial applications. I became interested in this field as the pilot of a single-seat Navy F/A-18, a highly automated and often difficult to understand aircraft with extremely narrow margins for mistakes. It was clear to me that future pilots will really be automation managers, and that principled research is needed to determine more effective forms of interaction.

Human supervisory control is an interdisciplinary field that includes: 1) the psychology of human decision making, which is critical in high risk, time-pressured systems, and often the limiting factor in system success, 2) computer science, specifically the design of algorithms (and resultant automation), as well as the interfaces that communicate with the operator (including aural, visual, and haptic), and 3) the engineering of the system that executes the task (e.g., it is important that a designer of a UAV cockpit understand how latencies in communication systems can negatively impact the human understanding and execution of a control mechanism). In addition, it is imperative to understand the systems engineering implications, as the human is linked, via various subsystems, to the physical control mechanism. This aspect is even more important as systems grow larger with increasing numbers of components and additional operators, such as in an air traffic control environment.

To facilitate my research, I formed the Humans and Automation Lab — HAL — under the auspices of the MIT Aeronautics and Astronautics Department.

CRITICAL SUPERVISORY CONTROL AREAS

The research I conduct within the human supervisory control domain primarily falls within two areas: decision support design and human-system performance evaluation. Both areas are critical for human supervisory control system development, since decision support tools allow operators to not only understand complex system states, but also how to interact with automated agents. Equally important is the development of metrics and tools for HSC assessment to ensure that design interventions are not only positively impacting human performance, but system performance as well. A significant part of this aspect of my research is the development of stochastic simulation-based system models that integrate both human and system models. These models are particularly useful in determining upper limits of human performance that will significantly impact overall system performance.

DECISION SUPPORT TOOLS ALLOW OPERATORS TO NOT ONLY UNDERSTAND COMPLEX SYSTEM STATES, BUT ALSO HOW TO INTERACT WITH AUTOMATED AGENTS.

In terms of decision support design, I am developing scheduling decision support tools for operators managing multiple complex tasks; specifically, multiple unmanned aerial vehicles. This effort examines the impact of increasing levels of automation of an operator’s ability to manage multiple complex tasks.

Adding more automation into a system is not necessarily better, since it can cause operator complacency as well as confusion in different modes of operation. I am examining how to visually represent time-critical, uncertain data with low cognitive overhead such that operators can more easily understand the effects of their actions on the current system, as well as what probable consequences of their actions on future system states.

I am also investigating innovative new decision support tool designs that span both visualization and aural displays. This includes NASA-sponsored research to determine how to provide effective path planning decision support for astronauts conducting traversals on the moon and Mars, as well as another NASA-sponsored effort to design the new lunar lander cockpit. The lunar lander display effort led to the development of a heads-up display component for vertically landing aircraft called the Vertical Altitude and Velocity Indicator. This display integrates information from multiple data sources in an easily understood format that promotes improved pilot performance while reducing training time. Displays embody more than visual components; my laboratory recently completed two studies focused on the HSC performance impact of sonifications (the combination of aural cues to represent numerical data for streamlined cognitive processing) and haptic cues (pressure vests and vibration sleeves).

Missy Cummings and student Sylvain Bruni work with innovative command and control mobile computer and communications equipment within the Humans and Automation Lab's Mobile Advanced Command and Control Station. (William Litant/MIT photograph)

ASSESSING HUMAN AND SYSTEM PERFORMANCE

Several projects are also underway to develop better metrics for human-system performance. In a research effort with Lincoln Laboratory, we have developed a set of three metric classes — attention allocation efficiency, interaction efficiency, and neglect efficiency — that

Aero-Astro students Lindley Graham (left) and Giselle DeAlmeida developing an eye-tracking testbed in Missy Cummings' Humans and Automation Lab. (William Litant/MIT photograph)

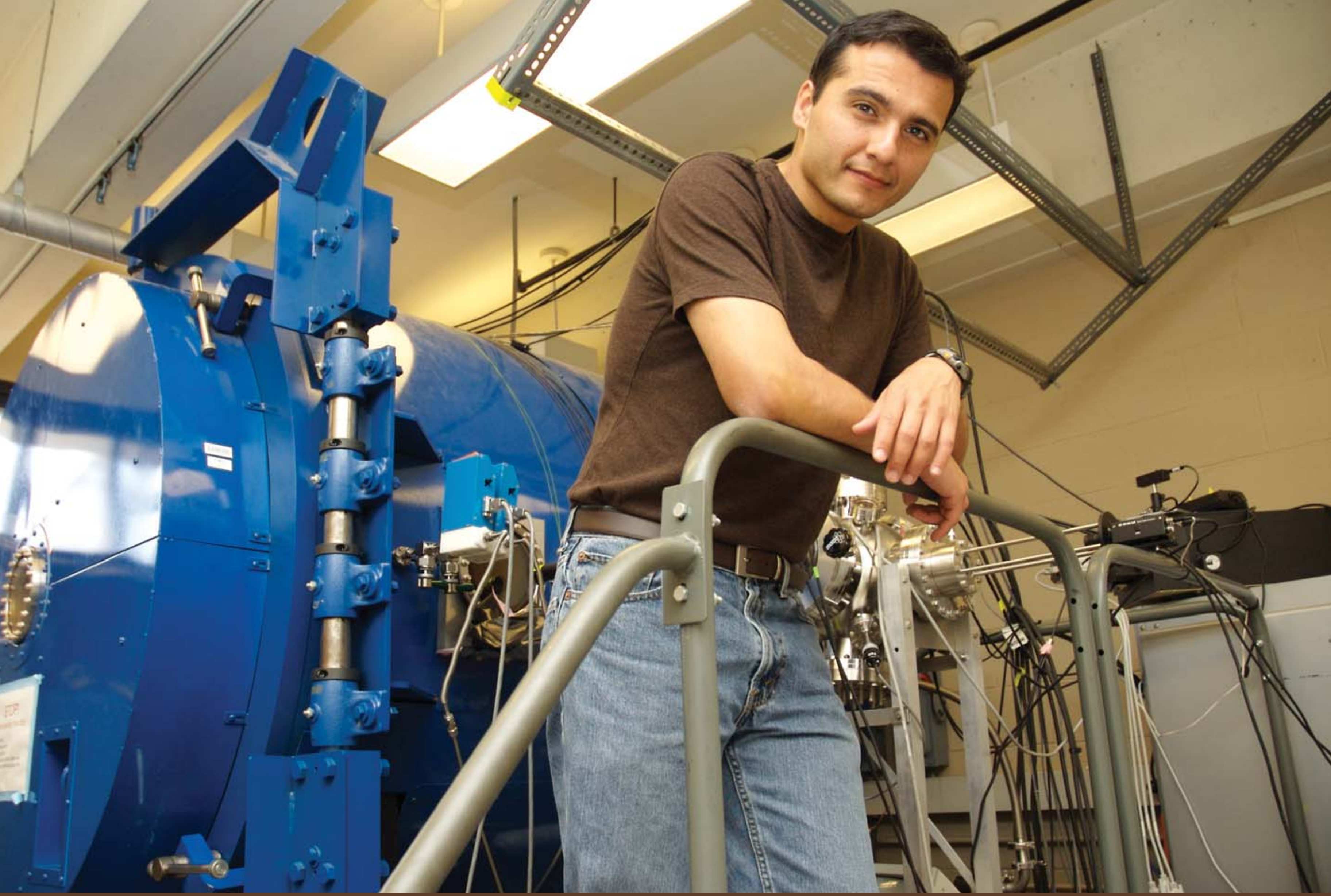
we propose, when taken together, can comprehensively assess human and system performance. This distinction is important because in human factors studies, researchers typically focus on just human performance, and not the overall impact of human control processes on the system state. In general, linking human and system performance beyond reaction time, subjective effort, and performance-based metrics has been difficult for researchers in the past, but our research shows promise, and potentially could revolutionize the way supervisory control systems are evaluated in the future. My goal is to develop metrics that can be used to assess human-system performance in real time to develop more robust, fault-tolerant systems that allow operator flexibility in decision making without compromising system safety.

Another important effort in terms of evaluation and metric development is the design of the Tracking Resource Allocation Cognitive Strategies tool, originally designed for an Office of Naval Research project. TRACS allows for the correlation of decision strategies with objective and subjective performance measures in resource allocation tasks, such as deploying a network of vehicles to deliver time-critical payloads, to determine the bounds of robust decision-making. It also can demonstrate where and how particular designs may or may not adequately support decision-making processes. While TRACS currently depicts a post-hoc visual representation of a user's decision-making processes while interacting with a multivariate optimization-based planning decision-support system, it is being modified to be used to predict, with some degree of uncertainty, when the performance of a user of a decision support system might degrade, and what the overall impact on the system would be. This kind of tool would be helpful to supervisors of groups of operators, such as the supervisor of air traffic controllers.

HAL research extends to many other domains, such as submarine and warehousing command and control center design, system architecture decision support tools, and the development of integrated displays for automobiles. The volume and growth rate of research is indicative of an overall systemic problem. Even the most elegantly designed systems will perform below expectations or fail unless human interactions are not taken into account. With the ever-growing demand for human-systems modeling-based approaches that enable design and evaluation of human supervisory control systems the outlook for my research and HAL is bright.

EVEN THE MOST ELEGANTLY DESIGNED SYSTEMS WILL PERFORM BELOW EXPECTATIONS OR FAIL UNLESS HUMAN INTERACTIONS ARE NOT TAKEN INTO ACCOUNT.

Mary (Missy) Cummings is an Associate Professor in Aeronautics and Astronautics at MIT and the director of the Humans and Automation Laboratory. She received her B.S. in Mathematics from the U.S. Naval Academy (1988), her M.S. in Space Systems Engineering from the Naval Postgraduate School (1994), and her Ph.D. in Systems Engineering from the University of Virginia (2003). A naval officer and military pilot from 1988-1999, she was one of the Navy's first female fighter pilots. Her teaching experience includes instructing for the Navy at Pennsylvania State University and as an assistant professor for the Virginia Tech Engineering Fundamentals Division. Her research interests include human interaction with autonomous vehicle systems, humans supervisory control, direct-perception interaction decision support design, human-computer interaction, and the ethical and social impact of technology. Missy Cummings may be reached at missyc@mit.edu.



In Aero-Astro's Space Propulsion Lab, Paulo Lozano is researching non-traditional configurations for Hall-effect plasma thrusters and their ability to propel spacecraft. (William Litant/MIT photograph)

FUTURE OF ROCKET ENGINES IS ELECTRIFYING

By Paulo Lozano

I decided to be a pilot, an engineer, a physicist, and a rocket scientist. Today, I have the privilege to say I am all four.

Many of us can pinpoint the exact moment when we decided what to do with our lives: during a trip, a conversation, reading a book, and so on. I was eight years old when my parents took me to the only operational planetarium in Mexico. Suddenly, I was confronted with physical processes that form stars, nebulae and galaxies, planets, and life. I was deeply affected by all these concepts. At that moment I knew I wanted to do something related to space science and exploration, something that would complement my already existing passion for airplanes and rockets. I decided to be a pilot, an engineer, a physicist, and a rocket scientist. Today, I have the privilege to say I am all four, and working at MIT's Department of Aeronautics and Astronautics allows me to move closer towards my lifelong dreams.

THE MOST EFFECTIVE ENGINES POSSIBLE

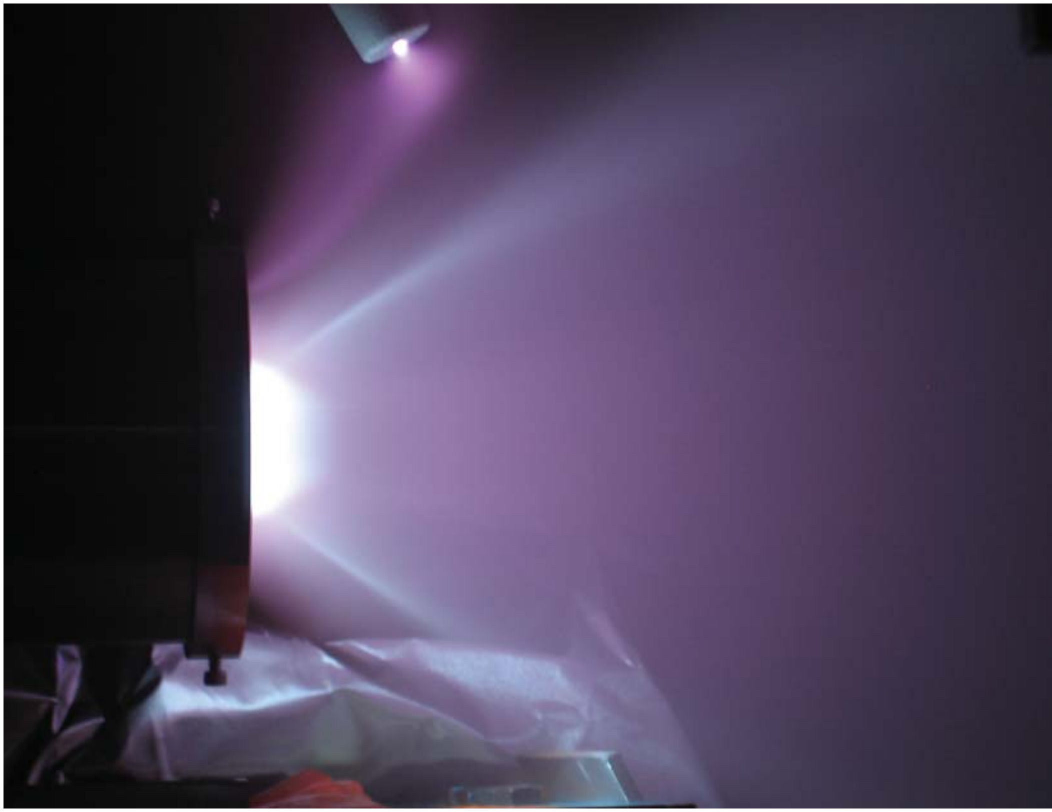
Philosopher Karl Popper said "All life is problem solving." This is the way we operate in our search to understand better the world we live in and to provide alternatives to improve the standard of living in the world. The problems I deal with in Aero-Astro's Space Propulsion Laboratory have to do with how we make the most effective rocket engine possible to carry valuable payload to different locations in space. For years, chemical-based rocket engines have dominated this technological area. However, there is a severe limitation; the thrust force they produce for every gram of propellant they use, or specific impulse, is somewhat low. This is the reason why in a mission that requires large changes in velocity, for instance a mission to explore the moons of Jupiter, most of the vehicle mass is propellant, leaving little room for payload. An elegant solution to this problem is to replace chemical reaction propulsion with direct propellant acceleration of electrically charged gas. Through this method, it is possible to increase the specific impulse of space thrusters 1000 percent, or even more. Propellant consumption becomes very efficient, reducing considerably its contribution to the total vehicle mass. Electric propulsion thrusters' sole limitation is the availability of onboard power. Since, in most cases, power comes from solar arrays, the thrust levels are small compared to chemical rockets. On the other hand, they can operate continuously for days or months, delivering a modest but constant acceleration that eventually makes the spacecraft move at large velocities — velocities practically unachievable for some missions using chemical engines.

ELECTRIC THRUST CAN OPERATE CONTINUOUSLY FOR DAYS OR MONTHS, DELIVERING VELOCITIES UNACHIEVABLE FOR CHEMICAL ENGINES.

At SPL, we are constantly looking for exciting ways to improve the state-of-the-art in space propulsion. For example, we are researching non-traditional configurations for Hall-effect plasma thrusters, which use magnetic fields to confine electrons that ionize gas through inelastic collisions, while ions are accelerated using electrostatic fields. As part of our undergraduate curriculum, some of our students are building a version of this engine for an eventual mission to the moon. Hands-on learning cannot be better than this! The engine uses permanent magnets and a conical geometry that departs significantly from traditional designs.

Interesting as plasma thrusters are, the focus of my research for the last few years has been on miniaturizing electric propulsion technologies. There are many reasons why this is important. Think in terms of the extraordinary achievements in micro- and nano-manufacturing that have boosted the electronics industry to a prominent place in the world

A conical shell plasma plume fires from a student-built space thruster in an Aero-Astro Space Propulsion Laboratory vacuum chamber. As electric thrusters' power comes from solar arrays, they can operate continuously for months, attaining velocities practically unachievable for missions using chemically-fueled engines.



economy. With today's techniques, we are miniaturizing communications, attitude, payload, control, power, and other subsystems of spacecraft. There is no apparent reason why a fully functional satellite the size of a hand-held MP3 player could not be built today — only missing from the equation is a comparably-sized propulsion subsystem that would allow the small object to perform for an extended period of time just as well as its heavyweight satellite cousins. Very small satellites, or clusters of them, could fill a niche market in communications, remote sensing, exploration, security, and other applications at a fraction of the launching and manufacturing costs of current platforms.

POWER FROM THE TIP OF A NEEDLE

EACH ONE OF THESE ION EMITTING TIPS PRODUCES A THRUST FORCE OF LESS THAN THE WEIGHT OF A HUMAN HAIR.

The propulsion technology I propose is based on the extraction and acceleration of ions from liquid surfaces, specifically from the liquid menisci located at the tip of micron-sized sharp needles. This is possible since the electric field on the surface of the liquid is amplified enormously to billions of volts per meter after the meniscus deforms into a stable cone-like structure. Ions are extracted through a quantum mechanics process and accelerate quickly to practically the full energy applied by the power supply, therefore operating at very high efficiencies. Each one of these ion emitting tips produces a thrust force of less than the weight of a human hair, whereas typical low power plasma engines push with a force several thousand times greater than this. Such a low thrust is not necessarily a weak point; in fact there are missions that require forces of that order to compensate for orbital perturbations, like high-altitude atmospheric drag or solar pressure. If higher thrusts are required, clusters of ion emitting tips working in parallel could be used. Since the individual size of these emitters is very small, they can be distributed on a surface in very tight arrangements. For example, the amount of thrust per unit area in such an array when spacing the emitters by one-third of a millimeter approximates that of a larger plasma thruster, and it becomes much larger for smaller separations. We use micro-fabricating techniques to produce arrays like this on different materials, like silicon and porous metals, and different geometries. Every component can be machined at the smallest of scales, thus producing a truly integrated propulsion subsystem that would scale with the rest of the spacecraft.

As an add-on to my research, we discovered that ion beams from these emitters are of such good quality that they can be used in other applications. For instance, we can use them as a source of monoenergetic, high-brightness negative ions for microscopy, lithography, implantation, mass spectrometry and others. As it turns out, these little liquid menisci provide a lot of material to do research on, experimentally and theoretically. I feel lucky to have encountered this topic on my way, and I look forward to the next big challenge in space propulsion.

Paulo Lozano is the Charles Stark Draper Assistant Professor of Aeronautics and Astronautics in the MIT Aeronautics and Astronautics Department. He holds an Ingeniero Fisico Industrial from ITESM, Mexico (1993); M.Sc. from CINVESTAV, Mexico (1996); and an S.M. (1998) and Ph.D. (2002) from MIT. His interests include electric propulsion, electrosprays, thruster physics, electrochemical microfabrication, engine health monitoring, and space mission design. He may be reached at plozano@mit.edu

Hamsa Balakrishnan's research is developing ways for next generation air transportation systems to run well in the face of increasing demands and external uncertainties.
(William Litant/MIT photograph)

PRACTICAL ALGORITHMS FOR AIR TRANSPORTATION SYSTEMS

By Hamsa Balakrishnan

The challenge lies in bridging the gap between theory and practice, and experience has taught us that overlooked operational issues often make theoretically sound ideas impractical.

These are truly exciting times for the air transport industry. The air transportation system, which began in the 1920s as a means of transporting passengers and mail among a handful of airports in the United States, has evolved into a large, complex system that interacts with global and regional economies, and which transports more than 2.1 billion passengers and 39 million tons of freight per year between almost 50,000 airports around the world. The steady increases in both passenger and cargo flights have led to an increase in flight delays, both in terms of the number of flights incurring delays and the total amounts of delay incurred, causing immense frustration to passengers and businesses. Moreover, with skyrocketing fuel prices, efficient air traffic operation has become more important than ever.

The demand for air traffic in the United States is expected to increase two- or three-fold over the next 15 years. Similar growth in demand is expected in Europe, while emerging markets such as China, India and the Middle East are expected to see a much larger demand spurt. With increasing demand comes reduced robustness to external conditions such as weather; for example, most of us have experienced flight delays flying from Boston to San Francisco because of weather in the Midwest.

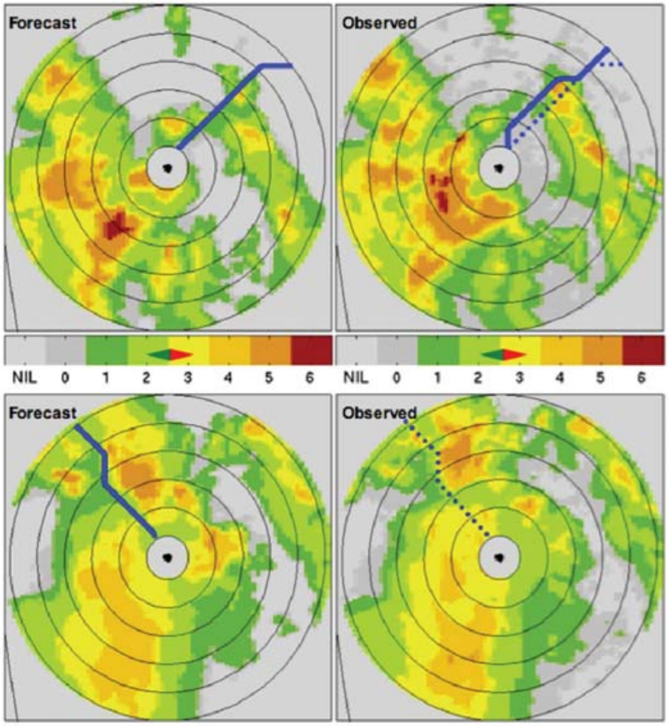
My research aims to develop methods for next generation air transportation systems to ensure that they will run well in the face of increasing demands and external uncertainties. My students and I develop practical, implementable algorithms backed by sound methodologies that aim to avoid catastrophic delays, gridlock, and environmental damage. These topics are both intellectually challenging and affect the way we live and work; this combination greatly motivates me.

My interest in air traffic management began when I was working toward my Ph.D. at Stanford University. My dissertation developed surveillance algorithms for tracking aircraft trajectories and maintaining knowledge of their identities. That experience, a subsequent stint at the NASA Ames Research Center, and my research at MIT over the past year and a half have shown me how concepts from diverse fields such as aeronautics, systems engineering, operations research, computer science, and economics, when combined cleverly, can dramatically improve the world's air transportation systems. In bringing together ideas from different fields to tackle fundamental air traffic challenges, my group collaborates with MIT, Lincoln Labs, and other groups.

COMPETITION, UNCERTAINTY, ENVIRONMENT IMPACT

What do we want from the air transportation system? Clearly, efficiency (accommodating as many flights as necessary with limited delays), robustness (avoiding situations in which unexpected weather in a small portion of the country results in widespread delays and rescheduling), and safety (minimizing the potential for accidents) are all of paramount importance. Achieving all these goals is difficult because of the size and complexity of the system. In addition to sheer size (31,000 flights a day in the United States alone), three important real-world issues must be dealt with: the presence of significant uncertainty, competition among the different stakeholders, and concerns regarding aviation's environmental impact.

In abstract terms, my work develops techniques that enable the efficient allocation of airspace and airport resources. These allocations are used to determine, for thousands of flights, the best departure times, the speeds to fly at, the routes to take and the optimal



Forecast weather (left) when a flight is 10 minutes from the outermost circle, and the actual weather (right) that materialized along routes into Atlanta airport at two different times on a day with significant convective weather. The outermost and the innermost rings are respectively 75 km and 10 km from Atlanta (the center of the circles). The distance between two consecutive circles represents about five minutes flying time. The colors denote the severity of convective weather: pilots generally avoid flying through Level 3 or greater weather. In the first case shown here, while the route determined in the forecast was actually impacted by weather, there was a route (solid line, top right) with limited deviation from the initial route that did not pass through adverse weather. This means that flights scheduled along that path could continue with only a minor modification to the path suggested by the forecast. In contrast, in the case shown at the bottom, any path that could avoid the weather that materialized would have required significant deviation from the original route. The forecast routes are denoted by dotted lines in the observed weather maps.

landing times. A good solution must recognize that when a flight departs from San Francisco, the arrival conditions at the time it reaches Boston (which depend on convective weather conditions, turbulence, icing, visibility, surface winds, etc.) have significant weather- and traffic-related uncertainties associated with them. Excessively conservative decisions, such as letting flights take off only when we are sure that a storm has dissipated, may mean that no flights land in Boston for hours after the weather clears, thereby causing unnecessary delays. Conversely, overly aggressive scheduling may mean that flights get to their destination before the storm clears, expending large amounts of time and fuel in holding patterns, even getting diverted to other airports, causing severe inconvenience to both passengers and the airlines.

These problems are not new, but my approach is different from previous research. Rather than treat each component of the system (e.g., route and schedule optimization, modeling weather uncertainty) in isolation, my methods bridge the gap among these different sub-problems by efficiently integrating information from various sub-problems into decision-making and robust optimization algorithms. The solutions to the sub-problems take the overarching system-level goals and context into account. For example, by comparing data from past aviation weather forecasts to the actual weather that materialized, we determine our ability to predict if a route will be blocked by a storm; using the stochastic weather models thus obtained, we can schedule traffic through the most viable routes in order to achieve robust operations. This approach avoids the pitfalls of prior efforts, which often resulted in robust route optimization algorithms that made invalid assumptions either about the uncertainty or about the information available in the weather forecasts.

MULTIPLE STAKEHOLDERS, COMPETING INTERESTS

The presence of multiple stakeholders and competing interests is an interesting challenge. The objectives themselves may differ among stakeholders; for example, on a weather-impacted day at a congested airport, air traffic control may be interested in maximizing the rate at which aircraft arrive and depart (the throughput), the airlines may be interested in minimizing either fuel costs, or the total delays incurred by them, or the delay incurred by high-priority flights, while travelers may care about the delay per passenger or the number of missed connections. These objectives are not necessarily aligned; for example, the schedule that maximizes throughput may not be the fuel-optimal or delay-optimal schedule. My solution is to develop techniques that determine the trade-offs among the different objectives to support traffic managers and airport operators in their decision-making.

AIRLINES COMPETE FOR AIRSPACE AND AIRPORT RESOURCES. SYSTEM-LEVEL PLANNING REQUIRES COOPERATION IN SCHEDULES AND REPORTING.

Another aspect of this issue that I address is that of airline competition. Airlines are inherently self-interested entities that compete for congested airspace and airport resources. System-level planning decisions require cooperation from the airlines in areas such as flight schedules, and mechanical delay and cancellation reports. Airlines are likely to cooperate only if they believe that the system is equitable and if an attempt is made to accommodate their preferences. Therefore, using concepts from game theory and mechanism design, we develop equitable scheduling algorithms and techniques for resource allocation (and reallocation) that incentivize information-sharing and truthful reporting by the airlines.

Aviation is one of the fastest growing contributors in the developed world to greenhouse gas emissions. The projected increase in air traffic demand is likely to make this worse; for this reason, there is growing regulatory and societal pressure to mitigate aircraft noise and emissions. My research aims at incorporating environmental objectives (e.g., the fuel burn or carbon emissions) into the problem of scheduling both airspace and airport ground operations, and determining what the potential trade-offs may be with other objectives such as system efficiency. The challenge lies in bridging the gap between theory and practice, and experience has taught us that overlooked operational issues often make theoretically sound ideas impractical. A recent example of this is Virgin Atlantic airline's widely publicized green initiative to potentially cut thousands of tons of carbon emissions by towing its Boeing 747s to the end of runways before departure: the program had to be suspended after Boeing determined that pulling the landing gear would seriously weaken it. My research investigates such potential operational barriers associated with current airport operations, including prevailing gate-use agreements and infrastructure constraints. In conjunction with such near-term efforts on operational improvements, I am also involved with research on reducing the environmental footprint of the airports of the future.

I believe that my research is an important step toward enabling safe, efficient, robust, and green air transportation. And that is ultimately what will make air travel fun once again for everyone!

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Nicholas Roy is developing intelligent estimation and planning algorithms that allow his robot dog to learn the shape of the ground via data from sensors such as the laser on its back. The dog applies the information to select footholds as it traverses rugged and uneven terrain. (William Litant/MIT photograph)

SOCIAL ROBOTS, SMART SYSTEMS

By Nicholas Roy

Decision-theoretic models and principled spatial and temporal reasoning will increasingly be an essential capability for any computational device that must operate for any length of time.

Unmanned vehicles that can deliberately move around and accomplish complex tasks without human intervention rely both on their knowledge of the world around them and their location in it. For example, even basic navigation and control largely requires external positioning systems such as GPS and pre-existing maps of the world. In indoor domains or the urban canyon, accurate maps and GPS are usually not available, greatly limiting the extent to which unmanned vehicles can be utilized in these domains. Unmanned air vehicles typically cannot fly autonomously in the urban canyon, and unmanned ground vehicle control often falls back on human operators.

My goals are to build unmanned vehicles that can fly without GPS through unmapped indoor environments and unmapped cities, to build social robots that can quickly learn what the user wants without being annoying or intrusive, and to build smart systems that know how to allocate their own computational resources. To accomplish this vision, I am developing intelligent inference and planning algorithms for autonomous unmanned vehicles that do not rely on external infrastructure, pre-existing maps or models. These algorithms will lead to robots that can immediately start autonomous operations with no prior information, automatically learning and adapting to the world around them in real-time, allowing them to be more easily deployed in new environments.

MAPPING CHALLENGES

However, a technical limitation is that most existing intelligent decision-making algorithms assume that the world is known accurately and precisely. For example, robotics has seen tremendous growth in the deployment of autonomous systems that can build their own robust models from partial or noisy sensor information. Statistical inference algorithms allow a robot to collect sensor data (such as camera images or range data) and assemble this data into a globally consistent map of the world. Once enough data has been collected and a complete and precise map has been generated, it can then be used by a robot to plan tasks and trajectories through the environment. Even though the mapping process understands how the effects of sensor noise and incomplete observations must be captured in the map, the underlying assumption of the planner is that the map is correct and complete. As a result, robotic planners often cannot be used with partial, incomplete, or uncertain maps. Furthermore, autonomous vehicles do not have a way to make decisions about how to complete the map, or even what additional information is needed for the task at hand.

Separating modeling and planning into two distinct processes has long simplified both problems, but for many domains, building complete and accurate maps becomes increasingly difficult, and the planner becomes susceptible to model errors. If the planner does not understand how to learn more about the world, the robot cannot plan sensing actions to improve its own performance. I refer to this problem as the "model-uncertainty" planning problem, where an autonomous vehicle must know how to make decisions with incomplete and uncertain knowledge as it learns about the world around it.

Previous work in this area has led to algorithms for efficient planning with restricted forms of uncertainty where the domain is small or the uncertainty has few degrees of freedom, allowing computationally efficient representations and solution techniques. However, planning in uncertain and incomplete models is a much larger class of problems, where the size and structure of the domain is much less tractable. As a result, my group is using machine learning techniques as a robust and computationally tractable way to address the model-uncertainty planning problem. Machine learning gives planning algorithms a way to find structure in this class of problems and form good policies, trading the additional cost of learning for dramatically reducing the cost of solving new problems. Learning requires substantial initial investment in training the system, but in most cases yields very fast responses after training. Learning can also be carried out incrementally, giving algorithmic robustness in domains that can change over time.

My group is applying these ideas in a variety of domains, given by the following example applications.

THE BELIEF ROADMAP ALGORITHM

One example problem my group has studied is trajectory planning for a micro air vehicle navigating indoors using a laser range finder of limited range to track its position. When the laser range finder cannot sense the local environment (e.g., in the middle of a large room), the vehicle can become lost and the vehicle velocity estimate can begin to drift substantially, leading both to errors in the desired trajectory and high-speed collisions with objects in the environment. By incorporating the uncertainty of the sensor data into the planning process using an algorithm known as the “belief roadmap” algorithm, we can construct large trajectories in high-dimensional spaces as efficiently as conventional trajectory planners that assume a known position estimate. The BRM algorithm allows the MAV to fly reliably and autonomously in locations that are normally inaccessible to unmanned air vehicles.

A second example problem is trajectory generation for vehicles exploring an unknown environment. When a robot is exploring a new environment, there is a natural tension between investigating as much of the environment as possible, and revisiting already-explored parts in the process of firming up the knowledge the robot already has. Balancing these two competing objectives is an optimization problem that cannot be solved efficiently. Instead, we have shown that reinforcement learning algorithms can be used to learn good exploration strategies from the robot's previous experience of different strategies. We are also applying this reinforcement learning technique to the problem of sensor trajectory planning in the weather domain to enable a team of UAVs making weather measurements

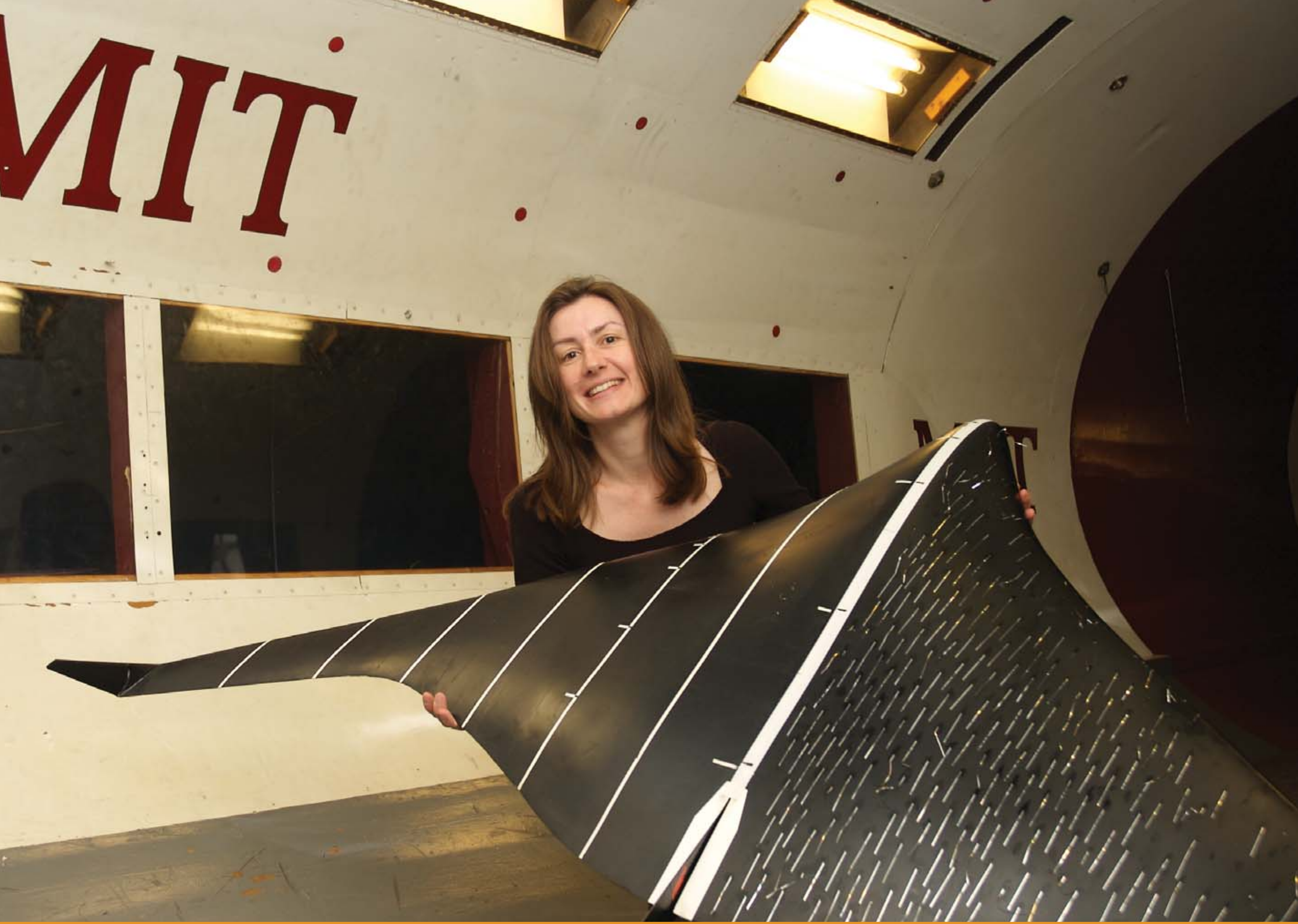
While Nicholas Roy looks on, grad student Ruijie He inspects an autonomous wheelchair, an intelligent assistive technology project under development in Roy's lab. The goal is to make assistive devices usable by a wider group of people with cognitive and physical deficits, and to develop smart interaction technologies that make the devices easier to use. (William Litant/MIT photograph)

to maximize the accuracy of prediction models. Furthermore, we are using related learning techniques to allow a quadruped robot to learn three-dimensional models of terrain from sensor data as it walks. This coupling of terrain model learning and planning allows legged robots to walk across rugged and uneven surfaces without prior maps of the terrain.

We have shown that the same technologies can be used to optimize a human-robot interaction system. We are developing a robotic wheelchair for use by people with limited motor control but high-level cognitive function. Our goal is to develop an intelligent dialogue system that can interact with a human in the wheelchair using natural language to understand what the human wants the wheelchair to do. While human-robot interaction may appear to be a dramatically different problem than map exploration, it can be framed as a model-uncertainty planning problem, where the sensor data is now a speech-recognition system, and the decision-making involves choosing how to respond to human requests. Existing dialogue interaction systems describe how to interact with people assuming a known behavioral model that includes vocabulary, word preferences, and how the user's intentional behaviors can change over time. If however, the model is inconsistent with the actual person's behavior, the robot may do exactly the wrong thing, leading to failures and user frustration. The objective of model-uncertainty planning in this domain is to learn a model of human behavior during dialogue with a robot. Given an initial, approximate estimate over possible behavior models, we can converge to a good estimate of user preferences more quickly and generate good dialogue policies. This allows us to generate dialog policies that are accurate with limited prior knowledge and minimal user training.

I intend to continue working on the issue of planning under uncertainty, motivated by autonomous vehicles in both remote and populated environments, but also with regard to a wide range of applications. In general, my research reflects the belief that decision-theoretic models and principled spatial and temporal reasoning will increasingly be an essential capability for any computational device that must operate for any length of time; there are many open questions, and, consequently, a great number of scientific challenges and opportunities.

Nicholas Roy is an Assistant Professor in the Massachusetts Institute of Technology Aeronautics and Astronautics Department. He received a B.Sc. and an M.Sc. from McGill University (1995 and 1997), and his Ph.D. from Carnegie Mellon University (2003). His specializations include robotics, machine learning, autonomous systems, planning and reasoning, and human-computer interaction. He may be reached at nickroy@mit.edu.



Real-time simulation and optimization is critical to the design of future aircraft such as blended-wing-body concepts like this one Karen Willcox holds in Aero-Astro's Wright Brothers Wind Tunnel. (William Litant/MIT photograph)

GETTING REAL*(TIME)* WITH SIMULATION AND OPTIMIZATION

By Karen Willcox

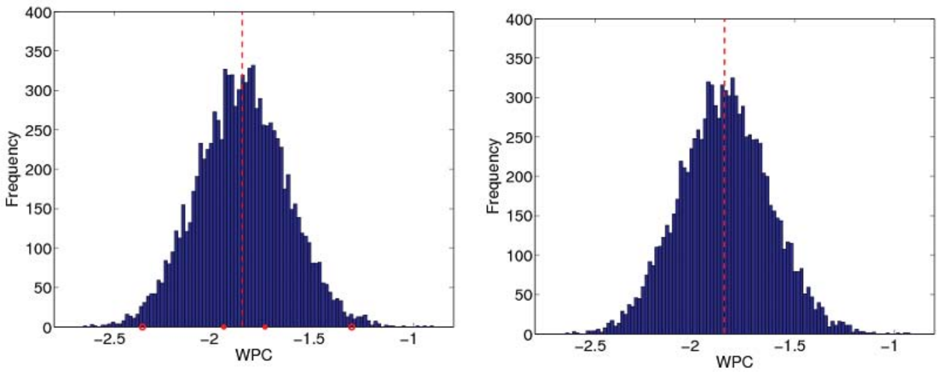
Computation for simulation and optimization is essential to the design and operation of aerospace systems. Improvements in computational methods, together with a substantial increase in computing power, have led to widespread use of high-fidelity methods, such as computational fluid dynamics, for analysis and design.

The next generation of computational methods must address the challenges of probabilistic design and simulation/optimization in real time. My research program is developing new approaches to address these challenges, with a broad set of applications ranging from active flow control, to turbomachinery aeroelasticity, to astronaut motion control, to tools to support international policy-making for aviation environmental impact.

CHALLENGES IN REAL-TIME SIMULATION AND UNCERTAINTY QUANTIFICATION

The need for simulation and optimization in real time is critical for many applications, including control of dynamical processes, adaptive systems, and data assimilation — that is, situations where real-time data must be assimilated with computational tools for rapid decision making. For example, one challenge related to homeland security applications is to solve a contaminant transport inverse problem on a grid of millions of cells, with limited measurements to determine the probable upstream source of a contaminant release, and the potential downstream impact areas — all within a few minutes to allow for emergency response.

Effective tools to support decision-making under uncertainty are also becoming essential in the design and operation of aerospace systems. This is particularly true as we move toward advanced technologies and unconventional aircraft configurations (i.e., unproven regions of the design space). To gain a sense of the immense challenge of carrying out probabilistic analysis with typical computational tools, consider two examples. The first example is quantification of the effects of manufacturing variations on the unsteady aerodynamic performance of a compressor in an aircraft engine — a problem critical to understanding and preventing engine high cycle fatigue. A simple linear two-dimensional CFD model of just a handful of blade rows might take just a few minutes to simulate a single blade geometry. However, to quantify uncertainty, we want to run Monte Carlo simulations, requiring the analyses of many thousands of different blade geometries. A Monte Carlo simulation with our simple model using 10,000 samples would translate into around three weeks of computation time. Even with simple models, the computational burden is immense; to tackle this problem with more sophisticated models that include nonlinearities, three-dimensional effects, or more blade rows is computationally intractable.



Monte Carlo simulations to compute the effects of blade geometric variations on work per cycle (measuring the unsteady aerodynamic loads on the blades). The same 10,000 random geometries were analyzed using the CFD model (left, 500 hours) and the reduced-order model (right, 0.2 hours). Joint work with T. Bui-Thanh and O. Ghattas.

The second example draws on computational models to support aviation environmental policy decision-making. Together with Professor Ian Waitz and a large international team of collaborators, I am working under the sponsorship of the FAA within the Partnership for AiR Transportation Noise and Emissions Reduction, an FAA Center of Excellence headquartered in Aero-Astro, to develop the Aviation Environmental Portfolio Management Tool, which will provide support to the international policy decision-making process through assessments of interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operations, and market scenarios. The scale and complexity of this problem is immense; for example, simulation of one year involves more than two million flights with 350 aircraft types, analyzed with black-box models spanning airline economics, environmental economics, aircraft operations, aircraft performance and emissions, noise, local air quality, and global climate. Furthermore, while just simulating the system is a daunting task, uncertainty must be characterized, computed and communicated in a way tangible to the domestic and international policy decision-makers.

MODEL REDUCTION

To tackle these real-time and uncertainty quantification challenges, we need a way to come up with more efficient system models — models that are much cheaper to solve, but retain high levels of predictive accuracy for the system dynamics of interest. This is often referred to as "surrogate modeling." My research focuses largely on model reduction, which uses mathematical techniques to exploit the structure of the system at hand in order to systematically generate surrogate models. With model reduction we can derive surrogate models for large-scale complex systems, with the benefit that the underlying mathematics and physics of the problem are driving the choice of reduced-order model.

For example, for active flow control of a supersonic inlet, we developed a new model reduction method to identify the important modes that describe the relationship between system inputs (control actuation, flow disturbances) and system outputs (describing the stability of the inlet). With this method, we can replace our CFD model of dimension 12,000 flow states (the unknown densities, velocities and pressures at each point in our computational domain) with a reduced-order model that has just 30 states, but retains very high accuracy for the specific input/output mappings of interest. This reduced-order model is a key enabler for achieving active control, which in turn enables the design of inlets that achieve efficiency gains by operating closer to stability margins.

We have also developed methodology that allows us to apply model reduction in settings where the system has many input parameters. In these cases, sampling the space of possible parameter variations is a considerable challenge that is not addressed by existing methods. The real-time contaminant transport inverse problem described above is one such setting—here, the input comprises the space of possible initial conditions, of which there are many thousands (or even millions). In collaboration with researchers at Sandia National Laboratories, we have demonstrated our approach on a model problem and are working to implement the method at full scale in Sandia tools. For the case of uncertainty quantification of the effects of manufacturing variations on the unsteady aerodynamic performance of a compressor, our approach yields an accurate reduced-order model that performs a Monte Carlo simulation in fewer than 15 minutes, compared to three weeks for the CFD code.

To ensure relevance and applicability to real-world problems, my research includes substantive engagement with government and industry. In 2006, I established the Research Consortium for Multidisciplinary System Design with Stanford University Professors Ilan Kroo and Juan Alonso.

EDUCATION

Perhaps one of my biggest surprises in joining the MIT faculty was to discover the problems that our undergraduate students have with mathematics. For example, poor abilities to apply concepts from differential equations can greatly hinder a student in understanding the key physical principles and central material of a controls course.

During my time on the MIT faculty, I have carried out educational research to address this issue, with a particular focus on creating better linkages between mathematics and engineering subjects. By working closely with faculty members in the mathematics department who teach freshman and sophomore required mathematics subjects, I established a process for explicit linking of mathematics courses and other mathematics resources in engineering courses. For Principles of Automatic Control (Course 16.06), I created a lecture-by-lecture mapping that details the specific mathematical skills required in each of my lectures and the associated upstream mathematics course where the concept was previously introduced or taught. I developed a set of supplementary mathematics notes and linkages to provide students with remedial resources for self-study and reference, and modified my lecture content to incorporate "flashbacks," or specific references to materials used in upstream mathematics courses. We have found that class performance shows that the combination of these notes and an increased emphasis on linkages during lecture helps considerably with students' grasp of underlying mathematical concepts. The supplementary notes appear to be an important resource—not for all students, but for those students who struggle with the underlying mathematics. In addition, I have worked with MIT OpenCourseWare to create an online version of the supplementary mathematics notes that provides direct links to online mathematics resources. This year, I moved teaching responsibilities from 16.06 to our Unified Engineering course; in the coming years I hope to have a chance to apply some of these ideas in Unified.

Karen Willcox is an Associate Professor in the MIT Aeronautics and Astronautics Department. Originally from New Zealand, she has a Bachelor of Engineering (Hons.) from the University of Auckland, and S.M. and Ph.D. degrees from MIT. She has been on the faculty at MIT since 2001. Prior to that, she worked at Boeing with the Blended-Wing-Body design group. In her spare time she climbs mountains and trains for ultramarathons. She may be reached at kwillcox@mit.edu.

Olivier de Weck with Experimental Projects (16.622) course students Brittany Baker (left) and Noelle Steber in Aero-Astro's Gelb Laboratory with their planetary rover reconfigurable wheel testbed. The wheel can change its shape to optimize drawbar pull and power consumption for varying soil conditions. (William Litant/MIT photograph)

STRATEGIC ENGINEERING: DESIGNING SYSTEMS FOR AN UNCERTAIN FUTURE

By Olivier de Weck

In engineering, customer requirements are traditionally gathered and frozen to help generate implementable designs. This is a proven approach for systems of low to moderate complexity. However, for large-scale engineering systems such as those critical to our aerospace, energy, and manufacturing industries, this can be a recipe for failure. Here is a striking example:

> *"Motorola unveils new concept for global personal communications: base is constellation of low-orbit cellular satellites."*
>
> Motorola Press Release on the Iridium Satellite System, London, June 26, 1990.

AND

> *"Iridium LLC seeks bankruptcy protection … Iridium has sapped more than $5 billion in resources from investors world-wide."*
>
> Wall Street Journal, New York, August 16, 1999

Thinking deeply about changeability will help us be more proactive about the design of future systems.

These quotes illustrate the dilemma. Iridium pioneered mobile satellite communications in the 1990s. It achieved many technological breakthroughs. Unfortunately, its original market forecasts and chosen capacity were confounded by the unexpected success of competing terrestrial cellular systems. The system's architecture was technically successful, but contributed to its commercial failure. In essence, the system became "locked" into a rigid configuration that had been chosen based on a "best guess" about an uncertain future.

I have found that the issue of having to design systems for uncertain future requirements is important and ubiquitous in many large-scale aerospace projects. This is why the focus of my research is the study of how complex systems and products evolve over time, and how they can be deliberately designed for changeability. Changeability is the degree to which a system can undergo modifications in its configuration without incurring large increases in its complexity and cost. Flexible systems are those that exhibit a high degree of changeability. Reconfigurable systems are the most flexible since they allow fast and reversible configuration changes.

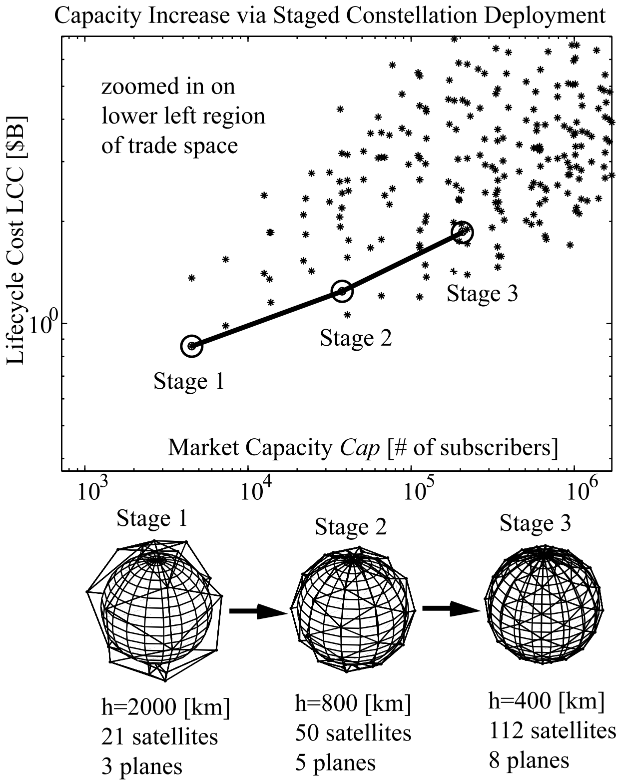
HOW CAN WE IDENTIFY CHANGES THAT ARE LIKELY TO PROPAGATE? ARE THERE GENERALIZABLE PRINCIPLES ACROSS MULTIPLE DOMAINS, OR MUST EACH ENGINEERING PROJECT BE TREATED AS A UNIQUE UNDERTAKING?

My experience in working on the redesign of the Swiss F/A-18 aircraft (1991-96) taught me that systems inevitably change. While the upgrading of avionics and software was relatively easy in this particular aircraft, modifications to the airframe turned out to be difficult. To certify the aircraft for 5,000 flight hours and flight loads up to 9g, we made changes to the baseline configuration. Some of these changes were well-behaved. Others, such as the substitution of titanium for aluminum in the three carry-through bulkheads, rippled through the system in complex ways. Unanticipated change propagation to other structures, manufacturing processes, and flight-control software added significant costs to the program. This experience sparked my interest in systems engineering and inspired my current research.

Increasingly, complex engineering systems have to account for partially unknown future requirements rather than being designed to a single "optimal" point. How can we identify changes that are likely to propagate? Are there generalizable principles across multiple domains, or must each engineering project be treated as a unique undertaking? Therein lays the challenge of my scientific quest.

FRAMEWORK FOR STRATEGIC ENGINEERING

Typically, the first step in designing a new system such as a passenger aircraft, satellite system, or launch vehicle is systems architecting. This involves understanding the underlying stakeholder structure and value flows, mission needs and possible range of requirements. During this phase various concepts are generated, evaluated and selected. The technical performance, lifecycle cost, value, and risk of a particular concept are usually only known approximately at this stage. The purpose of Integrated Modeling and Simulation is therefore to provide better estimates of system performance under both nominal (expected) and off-nominal conditions. Typically initial concepts are then further refined, and Multidisciplinary Design Optimization is used to fine-tune system configurations such that optimal designs, designated as $x^{\star}$, can be found.



A staged deployment strategy for constellations of communications satellites, and an example of planning for an uncertain future. The figure shows the optimal evolution path of a satellite constellation across three stages in terms of its lifecycle cost versus duplex channel capacity. (Olivier de Weck image)

The F/A-18 aircraft is an example of a highly capable multi-function machine with superb future growth potential and excellent lifecycle properties, such as maintainability and flexibility. (Beat Denier photograph)

Increasingly large aerospace systems are experiencing unexpected events and requirements shifts during their operations. Examples include the high price of aviation fuels, shifting customer needs from voice and video to data in satellite communications or an increased use of unmanned aerial vehicles for combat rather than pure surveillance missions. These uncertainties often require changes to the original system designs; that is, at some time $t=t_o+\Delta t$ the original configuration $x^\star$ is no longer optimal. If a system was designed such that it is very difficulty to change, it essentially becomes locked in to its original configuration. Systems are often changed retrospectively through retrofits or block upgrades in a reactive manner. This can be expensive and slow due to extensive change propagation effects as I experienced them on the F/A-18 program. Design for Changeability is a proactive approach to designing systems such that they can be “easily” changed by embedding flexibility in the original designs. This may in turn affect the choice of architecture and system decomposition as some architectures tend to be inherently more changeable than others.

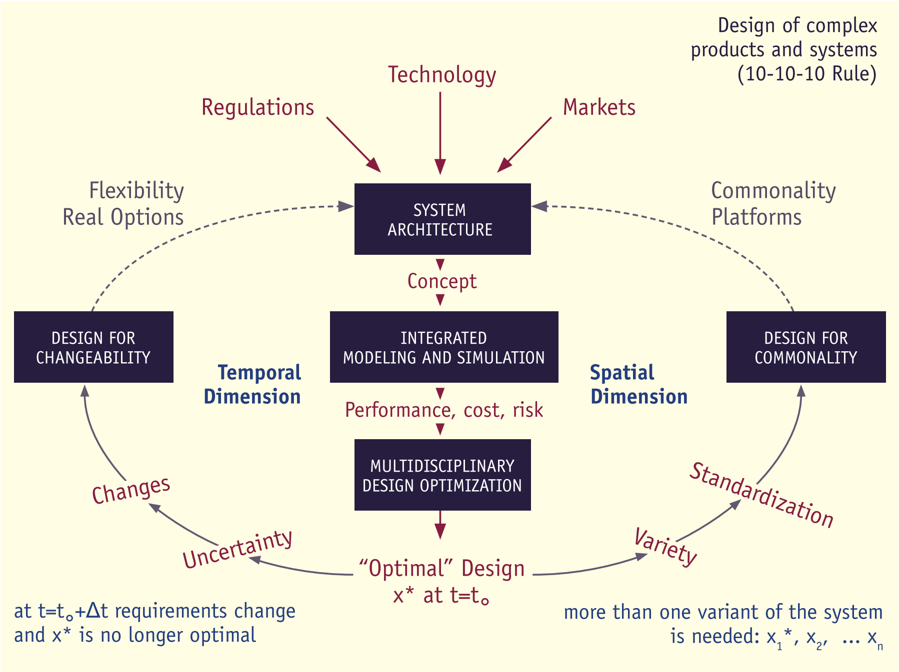
A second important observation is that many aerospace systems are no longer designed and produced individually, but as part of a larger ensemble such as a product family. Examples include the Boeing 787 family with variants such as the 787-8, 787-3 and 787-9, which differ primarily in terms of their range and passenger capacity. Satellite manufacturers are increasingly developing system variants from a common “bus” or platform. Design for Commonality attempts to maximize the overall value of systems and projects by identifying opportunities for commonality and partial standardization. This in turn feeds back on system architecture choices through platforms and the choice of system modularization.

DESIGNING FOR AN UNCERTAIN FUTURE

While strategic engineering is still an evolving area of research, the theoretical foundations and industrial applications have grown significantly in recent years. This is important when three conditions are present: long lifecycles, large irreversible investments, and significant requirements uncertainty. The core of my research is now focused on the development of generalizable methods that allow the incorporation of changeability and commonality considerations during systems architecting and design.

OUR ANALYSIS REVEALED THAT A REAL OPTION TO GROW CAPACITY IN STAGES CAN REDUCE LIFECYCLE COSTS BETWEEN 20-45 PERCENT RELATIVE TO A FIXED ALL-IN-ONE STRATEGY.

An early result was the development of staged deployment strategies for satellite constellations in response to the type of uncertainty that had been experienced by Iridium. Previous work had focused only on static constellation optimization for global Earth coverage with a minimum number of satellites. We adopted a very different approach from the traditional design method and found optimal evolution paths for satellite constellations based on calibrated technical-economic models. These results have been incorporated in courses



An overview of the "big picture," which articulates Olivier de Weck's view of his research areas in strategic engineering of systems and how they fit together.

such as 16.861 and ESD.36 and are assisting firms in the evaluation of the next generation of satellite constellations (e.g., Iridium Next).

As part of a project supported by Raytheon Integrated Defense Systems, we conducted a detailed analysis of more than 41,000 change requests on an engineering project. To everyone's surprise, we discovered a network of 2,600 changes that evolved over time during the eight-year development project of a complex radar system. This allowed us to isolate which subsystems were acting as multipliers or absorbers of change with the help of a new Change Propagation Index. Our time-expanded decision network methodology is perhaps one the most unifying contributions; it allows simulation and optimization of a system's evolution over time, by representing both the exogenous uncertainties and the decisions to reconfigure as an acyclic time-expanded network.

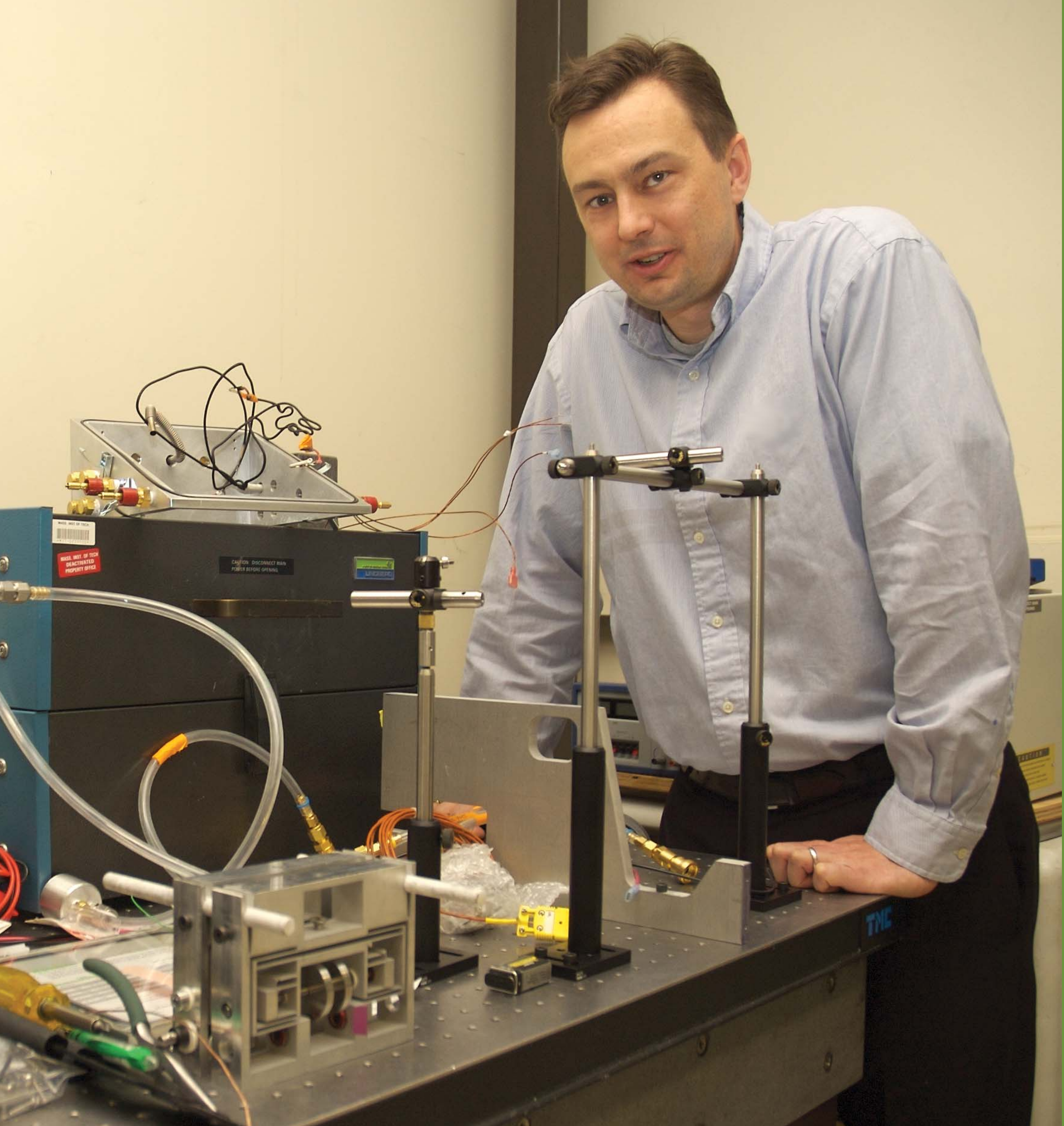
FUTURE VISION

Over the coming decades, billions of dollars will be invested in infrastructure renewal of vital large-scale systems. Globalization, technological innovation as well as regulatory, environmental and demographic changes drive large uncertainties, which must be reflected by the choice of appropriate system architectures and design solutions. A recent National Science Foundation workshop on complex systems acknowledged the changing and uncertain exogenous environment as an important phenomenon. The following research question was identified as one of the most important: “How can architectures enable resilient, adaptive, agile, evolvable systems?”

Together with my students and colleagues, I will continue to address the question of evolvability of systems and products over time. In addition to developing methods for designing new systems for changeability I want to study in more detail the past evolution of existing complex technical systems to understand which ones tended to be stable and which ones underwent significant changes, and why. Thinking deeply about changeability will help us be more proactive about the design of future systems.

> *“The engineer of 2020 will be faced with myriad challenges, creating offensive and defensive solutions at the macro- and microscales in preparation for possible dramatic changes in the world.”*
>
> The Engineer of 2020: Visions of Engineering in the New Century
> National Academy of Engineering, (2004), p.24

Olivier L. de Weck is an Associate Professor in the MIT Aero-Astro Department and Associate Director of the MIT Engineering Systems Division. His research interests are in Systems Engineering and Space Systems Design and Logistics. He has a Diplom Ingenieur degree in industrial engineering from the Swiss Federal Institute of Technology (1993) and a Ph.D. in Aerospace Systems from MIT (2001). From 1993 to 1997 he served as liaison engineer and, later, as engineering program manager for the Swiss F/A-18 program at McDonnell Douglas (now Boeing) in St. Louis. More information on his work may be found at http://strategic.mit.edu. He may be contacted at deweck@mit.edu



Brian Wardle in his lab with an experimental arrangement for synthesizing carbon nanotubes. (William Litant/MIT photograph)

NANO AND THE NEXT-GEN MATERIALS

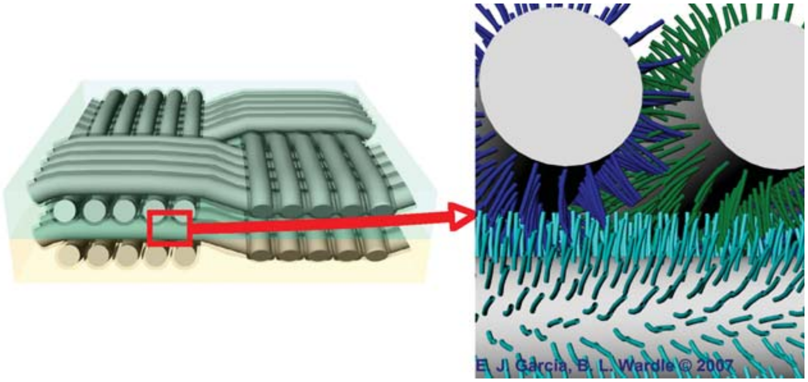
By Brian Wardle

While much work has been done to bring the nanoscale properties of carbon nanotubes to bear on macro-scale engineering materials and structures, little improvement in the performance of macro-scale structures had been gained despite nearly a decade's worth of research.

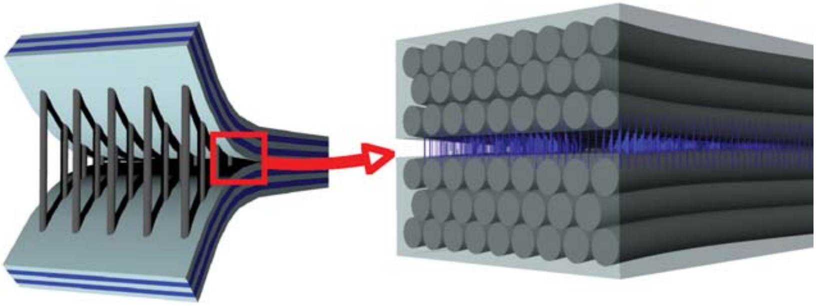
Recently, I was visiting an aircraft production line. I was suspended on a platform that allowed me to view the unfinished interior of a primary commercial transport structure made from advanced composites. The scientific and technical innovations to arrive at such a structure are at least 30 years in the making and represent efforts from the entire global advanced composites community.

After I reviewed technical aspects with the engineers leading the visit, I was both energized and left wondering how best to use this experience in the learning environments for my students.

I've been working in advanced aerospace structures, primarily in advanced composites, since my graduate work at MIT in the mid '90s. Since joining the Aero-Astro faculty, I have turned my group's attention to opportunities afforded by nano- and micro-structures, with a recent large effort in the areas of nanoscience and nanotechnology. While much work has been done to bring the nanoscale properties of carbon nanotubes to bear on macro-scale engineering materials and structures, little improvement in the performance of macro-scale structures had been gained, despite nearly a decade's worth of research. In 2003, my group started work on a new vision for using aligned carbon nanotubes (CNTs — perfect, hollow cylinders of carbon with exceptional physical properties) to enhance existing advanced composites. Advanced composites composed of aligned micron-diameter carbon fibers and polymers are prevalent in many aerospace applications. Rather than mixing nanometer-diameter CNTs into polymers in a random orientation, I envisioned working with CNTs as a second fiber



Fuzzy-fiber reinforced polymers are the nano-engineered version of carbon fiber reinforced plastics. FFRPs enhance existing advanced fiber and polymer composites with aligned carbon nanotubes, forming a three-dimensional nano-reinforced composite (left). Aligned-CNTs are grown in situ on the surface of woven advanced fiber cloth as a first step in the fabrication (right).



Nanostitched composites are existing aligned-fiber advanced composites reinforced at the weak ply interface with aligned CNTs. The processes developed for the nanostitch are compatible with existing composite processing routes.

to improve strength properties as well as provide multifunctionality. I conceived several hybrid architectures building upon existing advanced composite architectures and processing, using the aligned CNTs to attain new levels of performance.

We discovered that working with aligned CNTs not only makes sense for property tailoring and maximization, but it also allows for a new way of solving the difficult manufacturing challenges of dispersing and organizing CNTs into advanced polymers. (One does not want to start with 50 billion CNTs per square centimeter in a bag and then begin organizing them to make meter-scale structures!) Rather than mixing and/or organizing the CNTs, we grow aligned CNTs where they will have the desired engineering effect (e.g., in situ growth on woven fibers) and then impregnate with the polymer. My group has 15 people working on nano-engineered composite topics ranging from fabrication and characterization of standard mechanical samples, to probing nanoscale thermal and electrical transport properties in collaboration with groups in MIT Materials Science and Mechanical Engineering. We are performing both basic and applied research to address the physics, materials, processing, manufacturing, and mechanics challenges to realize these nano-engineered composites.

My group has built a significant presence in what we have termed “nano-engineered composites.” This idea brings together the promise of nanotechnology with practical and achievable approaches for implementing nanostructures in macrostructures, to achieve new levels of true multifunctional structural performance. We have recently demonstrated significant macroscopic (laminate-level) structural and electrical engineering property improvements. In mid-2007, I formed an aerospace industry consortium — Nano-Engineered Composite aerospace Structures — to build on a platform research. We will be working closely with nine industry partners for the next three years. Our hope is that we will enable the next-generation(s) of materials for aerospace and other demanding applications.

Macro-scale engineering property improvements provide a positive context in which to explore fundamental materials and physics questions regarding nanoscale interactions, and particularly how those aggregate to yield engineering-relevant macroscopic properties. An example is what happens when polymers crosslink in the presence of nanostructures, particularly when the nanostructures are closely spaced together. Consider that in some of the structures we have made, the CNT spacing is about 20 nm, which is on the order of the characteristic length of polymer chains. Many polymer scientists believe, and there is some evidence for this, that the polymers change character near the nanostructures and that, in fact, a secondary "interphase" polymer is created. We still don't know if this is true, but one of my group's new contributions is a novel experimental platform for fabricating articles to test this hypothesis. Helping to answer these fundamental scientific questions is both rewarding and enjoyable. However, as an engineer, I am still driven by practical considerations, such as how to optimally place the CNTs for improved structural performance.

Brian Wardle is the MIT Aeronatics and Astronautics Boeing Assistant Professor, He is pursuing research in nano-engineered advanced composites, power MEMS devices (fuel cells and vibrational energy harvesters), advanced composite systems durability and damage resistance/tolerance, and structural health monitoring technologies. He received a B.S. in Aerospace Engineering from Penn State University in 1992 and completed S.M. and Ph.D. work at MIT Aero-Astro in 1995 and 1998, respectively. He directs MIT's Nano-Engineered Composite aerospace STructures Consortium and is a principal member of the Technology Laboratory for Advanced Materials and Structures. He may be reached at wardle@mit.edu

Zoltan Spakovszky's research and passion center on challenges in energy, power, and propulsion. (William Litant/MIT photograph)

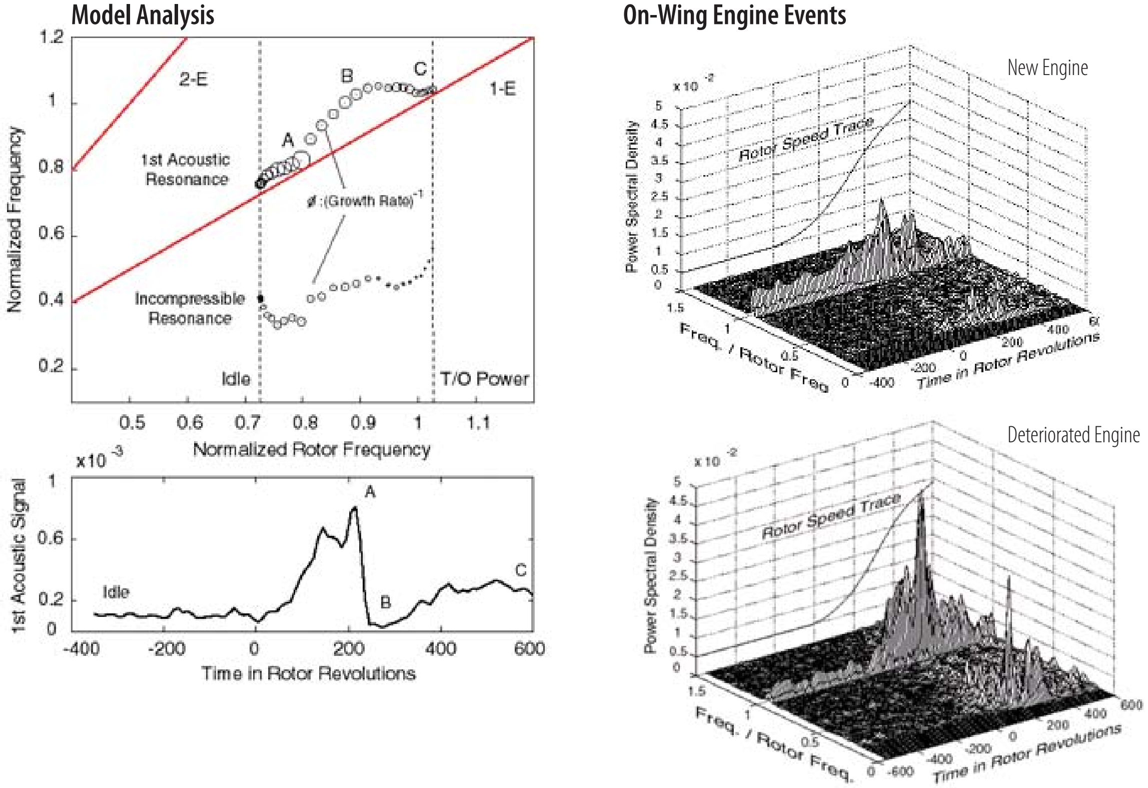
PASSION = VIBRATIONS AND WAVES IN TURBOMACHINERY

By Zoltan S. Spakovszky

The world of air-breathing propulsion is full of challenging problems where well-defined modeling goals can help tackle real and complex situations.

Since I was a child, the smell of unburned hydrocarbons from jet aircraft on the tarmac has sent a chill down my spine with the feeling that something exciting and powerful was going to happen.

After all these years, this passion has not faded. The first big step toward my childhood dreams of becoming an aeronautical engineer came true when finishing my Master's degree in Mechanical Engineering at ETH Zurich and working at Swissair Technics in the aircraft engine overhaul and maintenance services. This was the first time I got involved in solving a severe flow instability problem jeopardizing the safe operation of jet engines in service. This also brought me to the United States. After receiving my Ph.D. from the MIT Aeronautics and Astronautics Department in 2000, I joined GE Aircraft Engines as a lead engineer in the preliminary design and performance department. A short year later, I returned to MIT, and today, I still find myself attracted to research involving jet engines and turbomachinery. Undeniably, the field has evolved, but there will always be challenging problems in the energy, power, and propulsion fields that remain to be solved. G. F. Carrier, applied mathematician and National Medal of Science recipient, said of the future of engineering science, "There is still a multitude of worthwhile, unanswered questions in the world of natural sciences whose answers will ultimately be obtained with the help of mathematical tools and mathematical reasoning. Many of these will require a variety of heuristic arguments, the 'find it before you prove it exists' attitude, and the determination to understand the real phenomenon."


Model Analysis

On-Wing Engine Events

Computed acoustic resonance that can lead to engine surge (left) in agreement with acoustic pressure signals measured on wing in large commercial jet engines (right).

Characteristics of my research projects are that they are rich in concepts and ideas, entail first principles modeling for new insight of complex technological problems, focus on challenging problems important to society and supported by industry and government agencies, and involve team work and industry contacts.

Gas turbine jet engines can encounter a large variety of unsteady turbomachinery flow problems. Although unsteadiness in fluid motion is necessary for the work exchange in such machines (if the Beach Boys were aerodynamicists, they'd call these oscillations "the good vibrations"), the unsteady nature of fluid flow can be a real nuisance and can be manifested in detrimental vibrations and waves. These phenomena can limit the operating range (aerodynamic oscillations, and instabilities), induce structural failure and malfunction (mechanical vibrations), and generate noise (acoustics of fluid flow and structure interaction). The overarching theme that ties these diverse areas together is dynamic behavior and unsteadiness in fluids, and in fluid-structure interaction.

Following is a selection of turbomachinery problems where vibrations and waves are essential and where a dynamical system point of view proved successful in the modeling, analysis and the solution of the issues at hand.

UNSTEADY COMPRESSOR AERODYNAMICS AND STABILITY

Gas turbine engine performance is limited by flow instabilities known as surge and rotating stall, the mature forms of the natural oscillations of the fluid flow in the compression system. Surge is basically a circumferentially uniform pulsation of mass flow through the machine, while rotating stall appears as a reduced flow region in part of the circumference, which travels around the compressor annulus at a fraction of rotor speed. In-flight aero engine shut downs due to compressor instability happen on average in one out of 300,000 aircraft operations.

Together with Pratt & Whitney, I investigated and explained the mechanisms of observed unsteady flow phenomena in large civil aircraft engines. The work focused on the rigorous modeling of compressor stability loss due to engine deterioration and wear. Our analysis of stability during engine accelerations confirmed the mechanism of small-scale acoustic resonances seen in more than 360 aircraft engines in service. The results were useful for the development and improvement of an engine diagnostic and health monitoring test currently employed by airlines for fleet management purposes and now required by an FAA airworthiness directive.

AERODYNAMICALLY INDUCED TURBOMACHINERY ROTOR WHIRL

Non-uniform engine tip-clearance distributions, due, for example, to a compressor shaft offset from its casing centerline or whirling in its bearing journal, can induce destabilizing rotordynamic forces. These forces stem from the strong influence of the blade tip-clearance on the local performance of the compressor and can lead to destructive rotordynamic instabilities, potentially increasing engine fuel consumption by as much as 1 percent (for a major airline, this could amount to about $45 million of loss per year, given that fuel cost is about one-quarter of direct operating cost). Despite a large number of investigations of this topic over the past 40 years there has been disparity in the findings on the magnitude and direction of the whirl inducing force. To resolve this issue, in collaboration with GE Aircraft Engines experimenters I developed a theoretical model to explain observed rotordynamic-aerodynamic interaction mechanisms. The analysis showed that the direction of the whirl tendency is governed by the phase angle between the tip-clearance asymmetry and the blade loading distribution set by the flow turning and flow coefficient. Together with the new theory, the experiments resolved the long-standing whirl instability issues in compressors and turbines, and established a firm scientific basis for the observed phenomena. The findings are important for the development of next generation high-bypass ratio engines where lightweight structures and advanced engine architectures introduce new rotordynamic challenges.

QUIET AIRCRAFT TURBOMACHINERY AIR-BRAKE CONCEPT

Airports in key locations are operating at full capacity and the noise in the vicinity of airports is so intrusive that local communities object to any expansion. One example is a partially-constructed runway at Boston’s Logan Airport where construction was stopped by a court order and remains unfinished after 30 years. Aircraft on approach in high-drag and high-lift configuration create unsteady flow structures, which inherently generate noise. For devices such as flaps, spoilers, and the undercarriage, there is a strong correlation between overall noise and drag. In the quest for quieter aircraft, one challenge is to generate drag at low noise levels. We developed a novel drag concept, a so-called “swirl tube.” The idea is that a swirling exhaust flow (for example from an engine exhaust) can yield a streamwise vortex which is supported by a radial pressure gradient responsible for pressure drag and which will be quieter than conventional drag devices.

In collaboration with NASA Langley, we carried out detailed quantitative acoustic measurements, using a directional microphone array and a previously developed, state-of-the-art post-processing technique, to map acoustic sources. A scale model jet engine nacelle with stationary swirl vanes was designed and tested in the NASA Langley Quiet Flow Facility at full-scale approach Mach numbers. The analysis showed that the acoustic signature is comprised of quadrupole-type turbulent mixing noise from the swirling core flow scattering noise from vane boundary layers, and turbulent eddies of the burst vortex structure near sharp edges. The theory and the experiments, which were in agreement, demonstrated that low noise levels at high drag coefficients, comparable to that of bluff body drag, are, in fact, achievable.

The technological problems discussed above are different in nature and in disciplines but "vibrations and waves" form a common thread. In all three cases, the modeling focused on determining the dynamic behavior of the problem at hand. The approach is to simplify complicated problems to lay bare the underlying mechanisms.

The world of air-breathing propulsion is full of challenging problems where well-defined modeling goals can help tackle real and complex situations. As long as there are vibrations and waves at play, long shall live the eigenvalue — both with its real and imaginary parts.

Zoltan Spakovszky is the H. N. Slater Associate Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology and the director of the Gas Turbine Laboratory. He obtained his Dipl. Ing. degree in Mechanical Engineering from the Swiss Federal Institute of Technology (ETH) Zürich and his M.S. and Ph.D. degrees in Aeronautics and Astronautics from MIT. His principal fields of interest include internal flows in turbomachinery, compressor aerodynamics and stability, dynamic system modeling of aircraft gas turbine engines, micro-scale gas bearing dynamics, and aero-acoustics. Spakovszky may be reached at zolti@mit.edu.

Raúl Radovitzky's work is motivated by the critical need to understand explosion-induced blast waves on structures and humans. (William Litant/MIT photograph)

UNDERSTANDING EXPLOSIVE BLAST INJURIES WILL SAVE LIVES, IMPROVE TREATMENTS

By Raul Radovitzky

We have developed the most comprehensive model to date of the full human head containing all the relevant differentiated head and brain tissues and structures.

Blast attacks have become a primary threat in both military and civilian contexts. It is estimated that at least 10 percent of the soldiers deployed in Iraq and Afghanistan are affected by traumatic brain injury resulting from improvised explosive devices. Paradoxically, blast protection has only recently become an important consideration in the design of personal or vehicle armor, which, in the past, was primarily driven by ballistic protection. New IED-protective vehicles have proven effective for mitigating the IED effects, but they are extremely heavy and expensive.

In the context of civilian aviation security, improvements in explosive detection technology have reduced the detection thresholds to a point that aircraft hardening becomes conceivable and affordable.

In the last several years, my research has been motivated by the critical need to increase our understanding of the effects of blast waves on structures and humans; as well as to develop rational strategies for the design of blast protection material systems.

Toward this end, my group develops analytical and numerical tools for the analysis of complex blast physics phenomena. Examples include advanced algorithms and constitutive for material and tissue response to extreme loading conditions, coupled fluid-structure interaction models, and large-scale simulation codes for coupled adaptive multiphysics analysis.

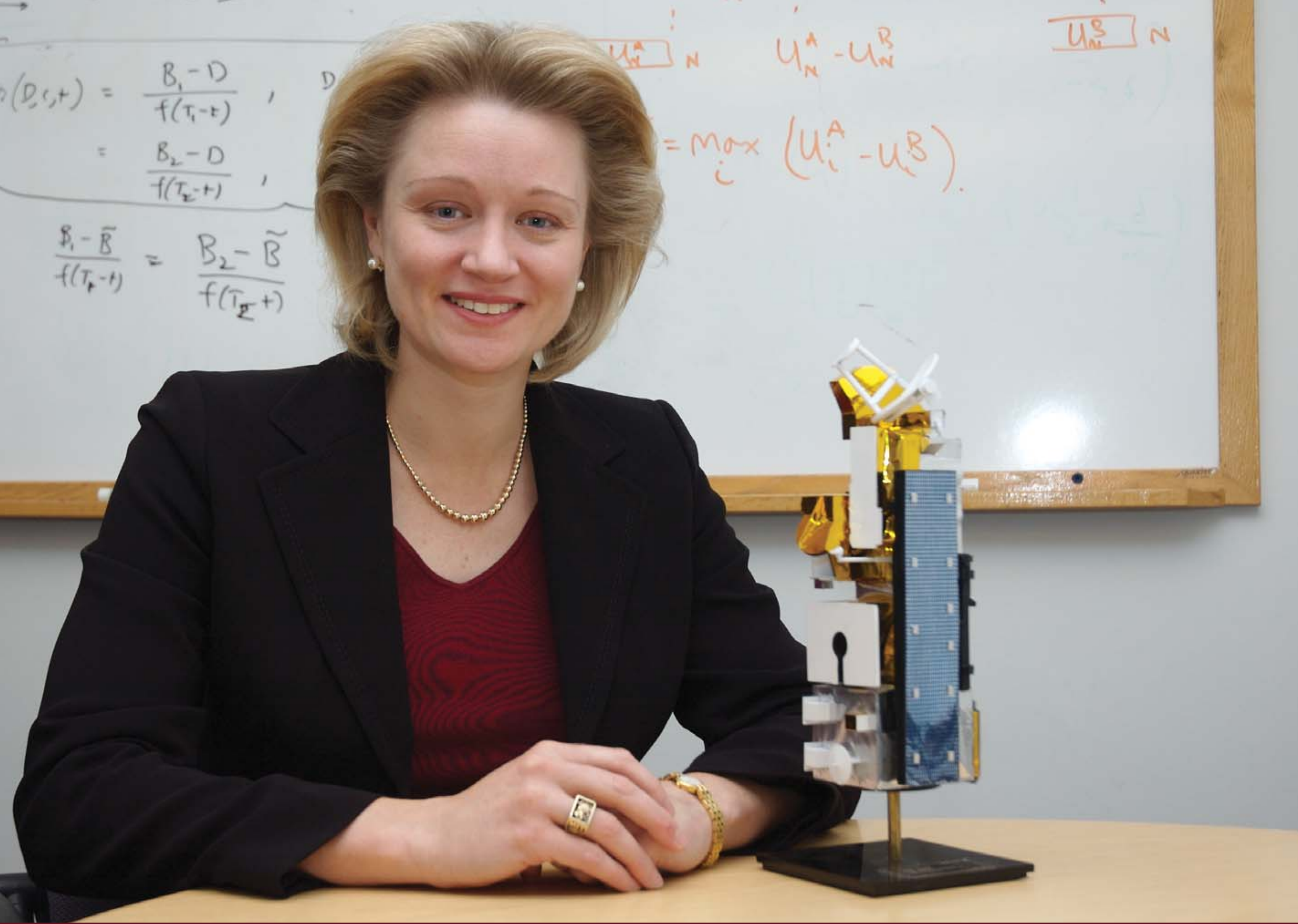
I have been leading the blast-protection research at the MIT Institute for Soldier Nanotechnologies where the emphasis has been on developing and optimizing the use of nanoengineered materials for protecting U.S. soldiers from blast threats. One of the main accomplishments in this activity has been an important theoretical result enabling the exploration of new strategies for air blast protection. The theory quantifies the fluid-structure interaction effect on the impulse transmitted by a blast wave to a structure in the presence of fluid compressibility, as is relevant in the case of airborne blast waves. It is found that the effect of compressibility is to exacerbate the impulse mitigation provided by fluid-structure interaction. This result is an important contribution to the understanding of blast loading of structures, which is now used by the blast research community.

I am also the MIT member of a team of faculty from University of Virginia; the University of California, Santa Barbara; Harvard; and Cambridge University developing cellular material concepts for force protection. As part of this Office of Naval Research Multidisciplinary University Research Initiative project, we have quantified passive and active approaches enabling prescribed mitigation levels.

Another main area of focus of my research has been on blast-related traumatic brain injury. I lead a multidisciplinary team of faculty and physicians from MIT, Purdue, the Hefner VA Medical Center, and the Defense and Veterans Brain Injury Center at the Walter Reed Army Medical Center focusing on traumatic brain injury caused by blast. This project, supported by the Department of Defense Joint IED Defeat Organization and the Army Research Office, is motivated by the high incidence of TBI produced by roadside bombs and IEDs in current conflicts, and aims to elucidate the physical and physiological mechanisms of injury to the brain at the cell and tissue level caused by blast waves. The goal is to develop a rational metric of blast injury and associated thresholds, which can then be used in combination with blast exposure sensing devices to aid in the clinical diagnostic and treatment of TBI, as well as in the conception and design of mitigation systems. As part of this project, we have demonstrated that the conditions the brain is subjected to during a blast event are well in excess of the threshold values of the accepted brain injury criteria for impact conditions. This suggests that the primary effects of a blast constitute a plausible cause for TBI. We have also developed the most comprehensive model to date of the full human head containing all the relevant differentiated head and brain tissues and structures. This model has been released to the medical and blast research community as the MIT/DVBIC Full Head Model.

As a result of this work, my group has established itself as one of the leading groups in blast-TBI research. Part of our leadership in this area has included my service as member of the Defense Science Board Improvised Explosive Devices Task Force Medical Panel, briefings to Senior DoD Leadership including the Army Surgeon General, the Navy Surgeon General and several Army Generals. Our work is also part of the 2007 Annual Report to Congress on the Efforts and Programs of the Department of Defense Relating to Prevention, Mitigation and Treatment of Blast Injuries.

Raúl Radovitzky is an Associate Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology. His interests include computational solid mechanics, mechanics of materials, and multi-scale modeling and simulation. He may be reached at rapa@mit.edu



Annalisa Weigel's research program was inspired by her MIT studies, her work in the defense department's Space Architect office, and by Carl Sagan.
(William Litant/MIT photograph)

LEARNING INNOVATION DYNAMICS IS KEY TO AEROSPACE CAPABILITY

By Annalisa L. Weigel

There are immense challenges in complex system architecture modeling and simulation, and in coordinating change among stakeholders.

I was 8 years old and watching Carl Sagan's "Cosmos" series on PBS. His journey through the marvels of the universe and the place of our tiny planet within it captivated me. I was hooked. Of course my interests have evolved some since then, but that was the initial spark that really set me on the path in aerospace that I'm on today.

The beginning of my formal education in aerospace began here at MIT where I was an undergraduate in Aero-Astro. Upon finishing my degree, I took a job with a small aerospace engineering consulting firm in the Washington, DC area. Luck and timing landed me an assignment in the center of an exciting new office in the Defense Department, called the Space Architect, tasked with creating and evaluating future architectures for space systems that spanned the military, intelligence, and civil space communities. I was exposed to the immense challenges involved in the modeling and simulation of complex system architectures, in coordinating change across multiple stakeholders with diverse interests, and in weaving considerations of policy into system design. I also became keenly aware of how much more we had yet to learn as a community of practitioners and scholars to better meet these challenges. And that's how I found myself back in graduate school and eventually joining the faculty, desiring to make an impact in these important areas.

My research program, inspired by these early experiences working on problems of both a technical and policy nature, is focused on three related themes: dynamics of complex systems architectural change and innovation in aerospace systems; the role of government in fostering aerospace innovation and change; and decision processes driving the policy and technical aspects of aerospace systems. However, understanding these dynamics, as well as the proper role for the government, holds the key to near- and long-term advancement of our aerospace system capabilities. And understanding decision processes underlying the technical and policy choices in the aerospace domain is a necessary foundation for this work.

THE DYNAMICS OF ARCHITECTURAL CHANGE AND INNOVATION SPECIFICALLY IN THE CONTEXT OF SPACE AND AIR TRANSPORTATION SYSTEMS IS POORLY UNDERSTOOD, AND HAS NOT BEEN THE FOCUS OF MUCH PREVIOUS SCHOLARLY WORK.

DISTRIBUTED SPACE SYSTEMS PROMISE FLEXIBILITY

In the space systems area, my research group is examining new distributed space system architectures that promise more flexibility for end users than current monolithic architectures. These new distributed architectures, dubbed “fractionated architectures” by DARPA, would break apart the subsystems and payload of a conventional spacecraft into several physically separated, free flying modules in proximity on orbit. One module might provide communications and data handling, another would provide power generation and storage, another might house the payload, and so on. We create physics-based parametric models to quantify the performance and flexibility of fractionated spacecraft architectures, and compare them to traditional monolithic architectures. We have found that fractionated architectures are more maintainable, scalable, adaptable, upgradeable, and flexible. And, under certain scenarios of large-scale deployment of fractionated architectures industry-wide, our cost modeling found that they may be cheaper than current monolithic architectures due to significant economies of scale.

But, taking a new architecture from concept to reality in the space arena requires more than just understanding its technical merits and user utility. Institutional barriers, organizational inertia, industry and market structure, and government policies and behaviors all play a

While performing engineering and technical analyses, Annalisa Weigel (center) and her students examine aerospace systems' political, economic, and social aspects. (William Litant/MIT photograph)

role in creating the environment in which architecture change and innovation take place. So, we complement our technical performance, user utility, and cost analysis of new space system architectures with descriptive and normative theory building about how innovation and architecture change happen for space systems. In the process of understanding the dynamics of change, we are trying to answer questions about the impact of the space system monopsony market structure on innovation, and how new architectures might change the market structure in ways favorable to innovation. We are also concerned with the complex mission-critical nature of space systems as a technical product, and how these characteristics differentiate innovation for space systems from the well-studied cases of innovation in simpler consumer products.

AIR TRANSPORTATION ARCHITECTURES EXAMINED

In the air transportation area, my research group is examining the architectural change dynamics of new airspace surveillance and communications architectures for air traffic control. The United States has just formally announced a move from radar-based surveillance to GPS-based surveillance with the mandate for Automatic Dependent Surveillance—Broadcast (ADS-B) technologies to be deployed throughout the national airspace control infrastructure by 2014, and required in aircraft by 2020. We draw on analytical methods from stakeholder analysis, network theory, game theory, and markets theory to construct models of airborne equipage and ground infrastructure transition. These models allow us to understand the distribution of costs and benefits among stakeholders where network effects are prominent, and examine policy and market mechanisms for more equitably aligning in time and scale the costs and benefits among stakeholders. We also explore the dynamics of architecture transition in a multi-stakeholder semi-regulated environment, examining the motivations of stakeholders, the effects of information asymmetries, and policy mechanisms that may work to resolve intransigence concerning architecture change.

At the end of the day, the results of our research aim to inform decision makers in both the government and industry sectors of the aerospace community about the dynamics of architecture change and innovation in the unique context of complex space and air transportation systems. Through deeper knowledge of these underlying innovation dynamics, better policies can be crafted to foster the change needed to continue to grow our aerospace system capabilities well into in the 21st century.

Annalisa Weigel is the Jerome C. Hunsacker Assistant Professor of Aeronautics and Astronautics and of Engineering Systems in the MIT Aeronautics and Astronautics Department. She received her S.B. and S.M. in Aeronautics and Astronautics at MIT, and her Ph.D. from MIT's Engineering Systems Division. Her research interests include aerospace policy, aerospace systems architecting and design, innovation and change dynamics in the aerospace industry, and systems engineering.

LAB REPORT: A Review of Aeronautics and Astronautics Department Laboratories

(Information provided by the Research Laboratories and Research Centers.)

Aerospace Controls Lab co-director Jon How (right) and his students with some of the vehicles they use in their autonomous system and control design research. (William Litant/MIT photograph)

Professor Mark Drela watches intently while Eleanor Yang Lin and Eric Liu laminate a wing structure in the Learning Lab's Gelb Laboratory. (William Litant/MIT Photograph)

THE AERO-ASTRO LEARNING LABORATORY

The Aero-Astro Learning Lab, which has been adopted as a model by other universities around the world, compliments the department's curriculum by provided spaces where students conceive, design, implement, and operate engineering systems in modern, team-based environments. The Learning Lab comprises four main areas. The **Arthur and Linda Gelb** Laboratory includes the Gelb Machine Shop, Instrumentation Laboratory, Mechanical Projects Area, Projects Space, and the Composite Fabrication-Design Shop. The Gelb Laboratory provides facilities for students to conduct hands-on experiential learning through diverse engineering projects. The Gelb facilities foster teamwork with a variety of resources (e.g., machining tools, electrical instrumentation, composites) to meet the needs of curricular and extracurricular projects. The **Gerhard Neumann Hangar** lets students work on large-scale projects that take considerable floor and table space. Typical of these projects are planetary rovers, a human-powered zero-g centrifuge, and UAVs. The structure also houses low-speed and supersonic wind tunnels. The **Robert C. Seamans Jr.** Laboratory includes a multipurpose room for meetings, presentations, lectures, videoconferences and distance learning. Two project offices support team study, group design work, online work, and telecommunication. A network operations area supports learning about the operations and management of networks. The Seamans Aerospace Library offers a collection of aerospace engineering resources with extensive digital information storage and retrieval capability. And, the Al Shaw Student Lounge provides a large space for social interaction and operations. The **Digital Design Studio** offers multiple computer stations arranged around reconfigurable conference tables. Here, students conduct engineering evaluations and design work, and exchange computerized databases as system and subsystem trades are conducted during the development cycle. Adjacent to the studio are the AA Department Design Room, and the Arthur W. Vogeley Design Room, which are reserved for student design teams.

Since its completion in 2001, the Learning Lab has spawned some of the departments' most interesting student projects including the Mars Biosatellite Project, a car competing for a 200 mpg X PRIZE, a successful competitor in the DARPA Urban Challenge, a legged planetary rover, and a flying automobile.

The Experimental Projects course (16.62x) is a major customer of the teaching labs including experiments and projects in the Neumann Hangar's low speed wind tunnel, and the workspaces in the Gelb Laboratory, with a number of excellent projects as outcomes. Two examples of work done in this hands-on environment are the investigation of reconfigurable wheels for planetary rovers and a study of bats' wing cilia enabling these creatures' highly maneuverable flight. The Neumann and Gelb facilities were also much used by the Robotics: Science and Systems I class, (16.415/6.14), which has participation from both Aero-Astro and Electrical Engineering and Computer Science faculty.

Another example of Learning Lab use is the Space Systems Engineering capstone class (16.83x, which is using the Gelb lab to build a high Delta-V (~2-3 km/sec) micro-satellite. The motivation is to provide a low cost orbital transfer vehicle capability for maneuvering throughout the Earth-moon system. The goal of the class is to deliver in May 2009, a flight qualified vehicle for launch as an ESPA-Ring (a device that permits up to six small satellites to be carried along with a larger satellite) secondary payload. The project offers approximately 45 undergraduates hands-on experience in designing, building, and testing actual flight hardware.

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

The Aerospace Computational Design Laboratory's mission is to lead the advancement and application of computational engineering for aerospace system design and optimization. ACDL research addresses a comprehensive range of topics in advanced computational fluid dynamics, methods for uncertainty quantification and control, and simulation-based design techniques.

The use of advanced computational fluid dynamics for complex 3D configurations allows for significant reductions in time from geometry-to-solution. Specific research interests include aerodynamics, aeroacoustics, flow and process control, fluid structure Interactions, hypersonic flows, high-order methods, multi-level solution techniques, large eddy simulation, and scientific visualization.

Uncertainty quantification and control is aimed at improving the efficiency and reliability of simulation-based analysis. Research is focused on error estimation and adaptive methods as well as certification of computer simulations.

The creation of computational decision-aiding tools in support of the design process is the objective of a number of methodologies the lab pursues. These include PDE-constrained optimization, real time simulation and optimization of systems governed by PDEs, multiscale optimization, model order reduction, geometry management, and fidelity management. ACDL is applying these methodologies to aircraft design and to the development of tools for assessing aviation environmental impact.

ACDL faculty and staff include: Jaime Peraire (director), David Darmofal, Mark Drela, Robert Haimes, Cuong Nguyen, Per-Olof Persson, Karen Willcox, and David Willis.

Visit the Aerospace Computational Design Laboratory at http://acdl.mit.edu/

AEROSPACE CONTROLS LABORATORY

The Aerospace Controls Laboratory researches topics related to autonomous systems and control design for aircraft, spacecraft, and ground vehicles. Theoretical research is pursued in areas such as decision making under uncertainty; path planning, activity and task assignment; estimation and navigation; sensor network design; and robust, adaptive, and model predictive control. A key part of ACL is RAVEN (Real-time indoor Autonomous Vehicle test ENvironment), a unique experimental facility that uses a Vicon motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, robust coordination algorithms for multiple helicopters, and vision-based sensing algorithms for indoor flight.

ACL was also involved in the 2007 DARPA URBAN Challenge and designed/developed the Rapidly-exploring Random Tree based motion planner and vehicle controller, which was integral to MIT's fourth-place finish in the competition.

ACL faculty are Jonathan How and Steven Hall.

Visit the Aerospace Controls Laboratory at http://acl.mit.edu/

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

The primary goal of the Communications and Networking Research Group is the design of network architectures that are cost effective, scalable, and meet emerging needs for high data-rate and reliable communications. To meet emerging critical needs for military communications, space exploration, and internet access for remote and mobile users, future aerospace networks will depend upon satellite, wireless and optical components. Satellite networks are essential for providing access to remote locations lacking in communications infrastructure; wireless networks are needed for communication between untethered nodes (such as autonomous air vehicles); and optical networks are critical to the network backbone and in high performance local area networks.

The group is working on a wide range of projects in the area of data communication and networks with application to satellite, wireless, and optical networks. An important aspect of the group's research is the development of architectures and algorithms that are optimized across multiple layers of the protocol stack, such as the design of network protocols that are aware of the physical layer channel conditions. For example, together with researchers at the Jet Propulsion Laboratory, the group recently demonstrated tremendous gains in network performance through the application of novel cross-layer resource allocation algorithms to Mars communications. The group's research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Eytan Modiano directs the Communications and Networking Research Group.

Visit the Communications and Networking Research Group at http://web.mit.edu/aeroastro/labs/cnrg/

COMPLEX SYSTEMS RESEARCH LABORATORY

Increasing complexity and coupling, and the introduction of digital technology, present challenges for engineering, operations, and sustainment. The Complex Systems Research Lab designs system modeling, analysis, and visualization theory and tools to assist in the design and operation of safer systems with greater capability. To accomplish these goals, the lab applies a systems approach to engineering that includes building technical foundations and knowledge and integrating these with the organizational, political, and cultural aspects of system construction and operation.

While CSRL's main emphasis is aerospace systems and applications, its research results are applicable to complex systems in such domains as transportation, energy, and health. Current research projects include accident modeling and design for safety, model-based system and software engineering, reusable, component-based system architectures, interactive visualization, human-centered system design, system diagnosis and fault tolerance, system sustainment, and organizational factors in engineering and project management.

CSRL faculty include Nancy Leveson (director), Mary Cummings, and Paul Lagace.

Visit the Complex Systems Research Laboratory at http://sunnyday.mit.edu/csrl.html

GAS TURBINE LABORATORY

The MIT Gas Turbine Laboratory has had a worldwide reputation for research and teaching at the forefront of gas turbine technology for more than 50 years. The GTL's mission is to advance the state-of-the-art in gas turbines for power and propulsion. The research is focused on advanced propulsion systems and turbomachinery, with activities in computational, theoretical, and experimental study of loss mechanisms and unsteady flows in turbomachines; compression system stability and active control; heat transfer in turbine blading; gas turbine engine noise reduction and aero-acoustics; pollutant emissions and community noise; and MEMS-based high-power-density engines.

Examples of past research includes the first implementation of a three-dimensional computation transonic compressor flow, and the concept of blowdown testing of transonic compressors and turbines, thereby enabling these machines to be used for university scale experiments. Recent examples are the work on turbomachine instabilities and "smart engines"; the research project on micro engine, which involves extensive collaboration with the MIT Department of Electrical Engineering and Computer Science; and the Silent Aircraft Initiative, which is a collaborative project with Cambridge University, Boeing, Rolls Royce, and other industrial partners to dramatically reduce aircraft noise below the background noise level in well-populated areas.

Zoltan Spakovszky is the GTL director. Faculty, research staff and frequent visitors include John Adamczyk, Nick Cumpsty, Fredric Ehrich, Alan Epstein, Edward Greitzer, Gerald Guenette, Stuart Jacobson, Bob Liebeck, Jack Kerrebrock, Choon Tan, and Ian Waitz.

Visit the Gas Turbine Lab at http://web.mit.edu/aeroastro/www/labs/GTL/index.html

HUMANS AND AUTOMATION LABORATORY

Research in the Humans and Automation Laboratory focuses on the multifaceted interactions of human and computer decision-making in complex socio-technical systems. With the explosion of automated technology, the need for humans as supervisors of complex automatic control systems has replaced the need for humans in direct manual control. A consequence of complex, highly-automated domains in which the human decision-maker is more on-the-loop than in-the-loop is that the level of required cognition has moved from that of well-rehearsed skill execution and rule following to higher, more abstract levels of knowledge synthesis, judgment, and reasoning. Employing human-centered design principles to human supervisory control problems, and identifying ways in which humans and computers can leverage the strengths of the other to achieve superior decisions together is HAL's central focus.

Current research projects include investigation of human understanding of complex optimization algorithms and visualization of cost functions, collaborative human-computer decision making in time-pressured scenarios (for both individuals and teams), human supervisory control of multiple unmanned vehicles, and designing decision support displays for direct-perception interaction as well as assistive collaboration technologies, including activity awareness interface technologies and interruption assistance technologies. Lab equipment includes an experimental test bed for future command and control decision support systems, intended to aid in the development of human-computer interface (HCI) design recommendations for future unmanned vehicle systems. In addition, the lab hosts a state-of-the-art multi-workstation collaborative teaming operations center, as well as a mobile command and control experimental test bed mounted in a Dodge Sprint van awarded through the Office of Naval Research.

HAL faculty include Mary Cummings (director), Nicholas Roy, and Thomas Sheridan.

Visit the Humans and Automation Laboratory at http://mit.edu/aeroastro/www/labs/halab/index.html

INTERNATIONAL CENTER FOR AIR TRANSPORTATION

The International Center for Air Transportation undertakes research and educational programs that discover and disseminate the knowledge and tools underlying a global air transportation industry driven by technologies. Global information systems are central to the future operation of international air transportation. Modern information technology systems of interest to ICAT include global communication and positioning; international air traffic management; scheduling, dispatch, and maintenance support; vehicle management; passenger information and communication; and real-time vehicle diagnostics.

Airline operations are also undergoing major transformations. Airline management, airport security, air transportation economics, fleet scheduling, traffic flow management, and airport facilities development, represent areas of great interest to the MIT faculty and are of vital importance to international air transportation. ICAT is a physical and intellectual home for these activities. ICAT, and its predecessors, the Aeronautical Systems Laboratory and Flight Transportation Laboratory, pioneered concepts in air traffic management and flight deck automation and displays that are now in common use.

ICAT faculty include R. John Hansman (director), Cynthia Barnhart, Peter Belobaba, and Amedeo Odoni.

Visit the International Center for Air Transportation at http://web.mit.edu/aeroastro/www/labs/ICAT/

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems is an interdepartmental research laboratory that began in 1939 as the Servomechanisms Laboratory, focusing on guided missile control, radar, and flight trainer technology. Today, LIDS conducts theoretical studies in communication and control, and is committed to advancing the state of knowledge of technologically important areas such as atmospheric optical communications, and multivariable robust control. In April 2004, LIDS moved to MIT's Stata Center, a dynamic space that promotes increased interaction within the lab and with the larger community. Laboratory research volume is approximately $6.5 million, and the size of the faculty and student body has tripled in recent years. LIDS continues to host events, notably weekly colloquia that feature leading scholars from the laboratory's research areas. The 12th annual LIDS Student Conference took place in January 2007, showcasing current student work and including keynote speakers. These, and other events reflect LIDS' commitment to building a vibrant, interdisciplinary community. In addition to a full-time staff of faculty, support personnel, and graduate assistants, scientists from around the globe visit LIDS to participate in its research program. Currently, 17 faculty members and approximately 100 graduate students are associated with the laboratory.

Aero-Astro / LIDS faculty includes Emilio Frazzoli and Moe Win. Vincent Chan directs the laboratory.

Visit LIDS at http://lids.mit.edu/

LEAN ADVANCEMENT INITIATIVE

The Lean Advancement Initiative is a unique learning and research consortium focused on enterprise transformation, and its members include key stakeholders from industry, government, and academia. LAI is headquartered in Aero-Astro, works in close collaboration with the Sloan School of Management, and is managed under the auspices of the Center for Technology, Policy and Industrial Development, an MIT-wide interdisciplinary research center.

LAI began in 1993 as the Lean Aircraft Initiative when leaders from the U.S. Air Force, MIT, labor unions, and defense aerospace businesses created a partnership to transform the U.S. aerospace industry using an operational philosophy known as "lean." LAI is now in its fifth and most important phase, and has moved beyond a focus on business-unit level change toward a holistic approach to transforming entire enterprises. Through collaborative stakeholder engagement, along with the development and promulgation of knowledge, practices, and tools, LAI enables enterprises to effectively, efficiently, and reliably create value in complex and rapidly changing environments. Consortium members work collaboratively through the neutral LAI forum toward enterprise excellence, and the results are radical improvements, lifecycle cost savings, and increased stakeholder value.

LAI's Educational Network includes 37 educational institutions in the United States, England, and Mexico and provides LAI members with unmatched educational outreach and training capabilities.

Aero-Astro LAI participants include Deborah Nightingale (co-director), Earll Murman, Dan Hastings, Annalisa Weigel, and Sheila Widnall. John Carroll (co-director) joins LAI from the Sloan School of Management, and Warren Seering and Joe Sussman represent the Engineering Systems Division.

Visit the Lean Aerospace Initiative at http://lean.mit.edu/

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory optimizes human-vehicle system safety and effectiveness by improving understanding of human physiological and cognitive capabilities, and developing countermeasures and evidence-based engineering design criteria. Research is interdisciplinary, and uses techniques from manual and supervisory control, signal processing, estimation, sensory-motor physiology, sensory and cognitive psychology, biomechanics, human factors engineering, artificial intelligence, and biostatistics. MVL has flown experiments on Space Shuttle missions, the Mir Space Station, and on many parabolic flights, and is developing experiments for the International Space Station. Research sponsors include NASA, the National Space Biomedical Institute, the Office of Naval Research, the Department of Transportation's FAA and FRA, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, and the MIT Portugal Program. Projects focus on advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity environments, spatial disorientation and navigation, teleoperation, design of aircraft and spacecraft displays, and controls and cockpit human factors. MVL students have been active in development of the Mars Gravity Biosatellite. Some of the MVL's newest research projects deal with the astronaut's role in semi-automatic lunar landing, mathematical modeling of spatial disorientation, assuring the effectiveness of astronaut lunar exploration sorties, planetary mission planning, microgravity teleoperation, fatigue detection, and advanced helmet designs for brain protection in sports and against explosive blasts. The MVL collaborates closely with the Harvard-MIT Program in Health Sciences and Technology, the Charles Stark Draper Laboratory, the Volpe Transportation Research Center, and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary. Annual MVL MIT Independent Activities Period activities include a course on Boeing 767 systems and automation.

MVL faculty include Charles Oman (director), Jeffrey Hoffman, Dava Newman, and Laurence Young. They teach subjects in human factors engineering, space systems engineering, space policy, flight simulation, space physiology, aerospace biomedical engineering, the physiology of human spatial orientation, and leadership. The MVL also serves as the office of the Director for the NSBRI-sponsored Graduate Program in Bioastronautics, the Massachusetts Space Grant Consortium, NSBRI Sensory-Motor Adaptation Team, the MIT-Volpe Program in Transportation Human Factors, and the MIT Portugal Program's Bioengineering Systems focus area.

Visit the Man Vehicle Laboratory at http://mvl.mit.edu/

THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for AiR Transportation Noise and Emissions Reduction is an MIT-led FAA/NASA/Transport Canada-sponsored Center of Excellence. PARTNER fosters breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment. PARTNER combines the talents of 10 universities, three federal agencies, and 53 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups. During 2007-08, PARTNER continued to expand its research portfolio and added advisory board members. New research projects include Health Effects of Aircraft Noise, Emissions Characteristics of Alternative Aviation Fuels, Airport Surface Movement Optimization, and Network Restructuring Scenarios for ATO Forecasts. New advisory board members are the Air Line Pilots Association, Commercial Aviation Alternative Fuels Initiative, International Airline Passengers Association, Opportunities for Meeting the Environmental challenge of Growth in Aviation, and the Federal Interagency Committee on Aviation Noise. Several new research reports were released including a low-frequency noise impact study, a land-use and noise complaint study, a passive sound insulation report, and a vibration and rattle mitigation report.

MIT's most prominent role within PARTNER is developing research tools that provide rigorous guidance to policy-makers who must decide among alternatives to address aviation's environmental impact. The MIT researchers collaborate with an international team in developing aircraft-level and aviation system level tools to assess the costs and benefits of different policies and R&D investment strategies.

Other PARTNER initiatives in which MIT participates include exploring mitigating aviation environmental impacts via the use of alternative fuels for aircraft; studies of aircraft particulate matter microphysics and chemistry; and a study of reducing vertical separations required between commercial aircraft, which may enhance operating efficiency by making available more fuel/time efficient flight levels, and enhancing air traffic control flexibility and airspace capacity.

PARTNER MIT personnel include Ian Waitz, who directs the organization, Stuart Jacobson (associate director), Hamsa Balakrishnan., John Hansman, James Hileman, Karen Willcox, Malcom Weiss, Stephen Connors, William Litant (communications director), Jennifer Leith (program coordinator), and 10-15 graduate students.

Visit The Partnership for AiR Transportation Noise and Emissions Reduction at http://www.partner.aero

SPACE PROPULSION LABORATORY

The Space Propulsion Laboratory, part of the Space Systems Lab, studies and develops systems for increasing performance and reducing costs of space propulsion. A major area of interest to the lab is electric propulsion in which electrical, rather than chemical energy propels spacecraft. The benefits are numerous, hence the reason electric propulsion systems are increasingly applied to communication satellites and scientific space missions. In the future, these efficient engines will allow exploration in more detail of the structure of the universe, increase the lifetime of commercial payloads, and look for signs of life in far away places. Areas of research include Hall thrusters; plasma plumes and their interaction with spacecraft; electrospray physics, mainly as it relates to propulsion; microfabrication of electrospray thruster arrays; Helicon and other radio frequency plasma devices; and space electrodynamic tethers. Manuel Martinez-Sanchez directs the SPL research group, and Paulo Lozano and Oleg Batishchev are key participants.

Visit the Space Propulsion Laboratory at http://web.mit.edu/dept/aeroastro/www/labs/SPL/home.htm

SPACE SYSTEMS LABORATORY

Space Systems Laboratory research contributes to exploration and development of space. SSL's mission is to explore innovative space systems concepts while training researchers to be conversant in this field. The major programs include systems analysis studies and tool development, precision optical systems for space telescopes, microgravity experiments operated aboard the International Space Station, and robotic operations for Mars and beyond. Research encompasses a wide array of topics that together comprise a majority of space systems: systems architecting, dynamics and control, active structural control, thermal analysis, space power and propulsion, microelectromechanical systems, modular space systems design, micro-satellite design, real-time embedded systems, and software development.

Major SSL initiatives study the development of formation flight technology. The SPHERES facility, which began operations aboard the International Space Station in May 2006, enables research of algorithms for distributed satellites systems, including telescope formation flight, docking, and stack reconfiguration. The Electromagnetic Formation Flight testbed is a proof-of-concept demonstration for a formation flight system that has no consumables; a space-qualified version is under study. The MOST project studies multiple architectures for lightweight segmented mirror space telescopes using active structural control; its final product will be a ground-prototype demonstrator. Multiple programs research the synthesis and analysis of architectural options for future manned and robotic exploration of the Earth-Moon-Mars system, as well as real options analysis for Earth-to-Orbit launch and assembly. SSL continues to lead the development of methodologies and tools for space logistics. In 2007, SpaceNet 1.4 was accredited by the NASA Constellation Program as an approved software tool for modeling lunar exploration missions and campaigns. SSL contributed several important studies to the Constellation Program Integrated Design and Analysis Cycles. Together with the Jet Propulsion Laboratory, SSL is editing a new AIAA Progress in Aeronautics and Astronautics Volume on Space Logistics that summarizes the current state of the art and future directions in the field. Jointly with Aurora Flight Sciences SSL is developing prototypes for automated asset tracking and management systems for ISS based on radio frequency identification technology. Innovative exploration logistics container concepts were tested at the Mars Desert Research Station in Utah in February 2008.

SSL personnel include David W. Miller (director), John Keesee, Olivier de Weck, Edward F. Crawley, Daniel Hastings, Annalisa Weigel, Manuel Martinez-Sanchez, Paulo Lozano, Oleg Batishchev, Alvar Saenz-Otero, Paul Bauer, SharonLeah Brown (administrator and outreach coordinator), Brían O'Conaill (fiscal officer), and Marilyn E. Good (administrative assistant).

Visit the Space Systems Laboratory at http://ssl.mit.edu/

TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES

A dedicated and multidisciplinary group of researchers constitute the Technology Laboratory for Advanced Materials and Structures. They work cooperatively to advance the knowledge base and understanding that will help facilitate and accelerate the advanced materials systems development and use in various advanced structural applications and devices.

The laboratory has broadened its interests from a strong historical background in composite materials, and this is reflected in the name change from the former Technology Laboratory for Advanced Composites. A new initiative involves engineering materials systems at the nanoscale, particularly focusing on aligned carbon nanotubes as a significant constituent in new materials and structures. This initiative is in partnership with industry through the Nano-Engineered Composite aerospace STructures (NECST) Consortium. The research interests and ongoing work in the laboratory thus represent a diverse and growing set of areas and associations. Areas of interest include:

- nano-engineered hybrid advanced composite design, fabrication, and testing
- characterization of carbon nanotube bulk engineering properties
- composite tubular structural and laminate failures
- MEMS-scale mechanical energy harvesting modeling, design, and testing
- durability testing of structural health monitoring systems
- thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization
- continued efforts on addressing the roles of lengthscale in the failure of composite structures
- numerical and analytical solid modeling to inform, and be informed by, experiments
- continued engagement in the overall issues of the design of composite structures with a focus on failure and durability, particularly within the context of safety

In supporting this work, TELAMS has complete facilities for the fabrication of structural specimens such as coupons, shells, shafts, stiffened panels, and pressurized cylinders, made of composites, active, and other materials. A recent addition includes several reactors for synthesizing carbon nanotubes. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility. TELAMS maintains capabilities for environmental conditioning, testing at low and high temperature, and in hostile and other controlled environments. There are facilities for nano and microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization.

With its, linked, and coordinated efforts, both internal and external, the laboratory continues its commitment to leadership in the advancement of the knowledge and capabilities of the composites and structures community through education of students, original research, and interactions with the community. There has been a broadening of this commitment consistent with the broadening of the interest areas in the laboratory. This commitment is exemplified in the newly formed NECST Consortium, an industry-supported center for developing hybrid advanced polymeric composites. In all these efforts, the laboratory and its members continue their extensive collaborations with industry, government organizations, other academic institutions, and other groups and faculty within the MIT community.

TELAMS faculty include Paul A. Lagace (director), Brian L. Wardle, and visitors Antonio Miravete and Leonard Daniel.

Visit the Technology Laboratory for Advanced Materials and Structures at http://web.mit.edu/telams/index.html and the Nano-Engineered Composite aerospace STructures Consortium at http://necst.mit.edu.

WRIGHT BROTHERS WIND TUNNEL

Since its opening in September 1938, The Wright Brothers Wind Tunnel has played a major role in the development of aerospace, civil engineering and architectural systems. In recent years, faculty research interests generated long-range studies of unsteady airfoil flow fields, jet engine inlet-vortex behavior, aeroelastic tests of unducted propeller fans, and panel methods for tunnel wall interaction effects. Industrial testing has ranged over auxiliary propulsion burner units, helicopter antenna pods, and in-flight trailing cables, as well as concepts for roofing attachments, a variety of stationary and vehicle mounted ground antenna configurations, the aeroelastic dynamics of airport control tower configurations for the Federal Aviation Authority, and the less anticipated live tests in Olympic ski gear, space suits for tare evaluations related to underwater simulations of weightless space activity, racing bicycles, subway station entrances, and Olympic rowing shells for oarlock system drag comparisons.

In its nearly 70 years of operations, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

Visit the Wright Brothers Wind Tunnel at http://web.mit.edu/aeroastro/www/labs/WBWT/wbwt.html