AEROASTRO

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AEROASTRO

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DESIGN

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Cover: Aboard NASA's C-9 Reduced Gravity Research Program aircraft, Professor Dava Newman performs the Man Vehicle Lab's MICRO-G experiment, an investigation of zero gravity crew reactions. To the left is grad student Phil Ferguson and to the right is Professor Karen Willcox. MVL researchers were quantifying astronaut push off and landing loads, and measuring adaptation to the weightless environment in terms of motor control strategies and adaptation. The lead author of a paper on the research (Stirling, L., Willcox, K., Ferguson, P., Newman, D.J., "Kinetics and Kinematics for Translational Motions in Microgravity During Parabolic Flight," Journal of Aviation, Space Environmental Medicine, vol. 80, No. 6, pp. 522-531, 2009) was grad student Leia Stirling who has since joined AeroAstro as an assistant professor. (NASA)

The Man Vehicle Lab recently celebrated its 50th anniversary. See "The Man Vehicle Lab at 50" on page 55.

THE FUTURE IS BRIGHT

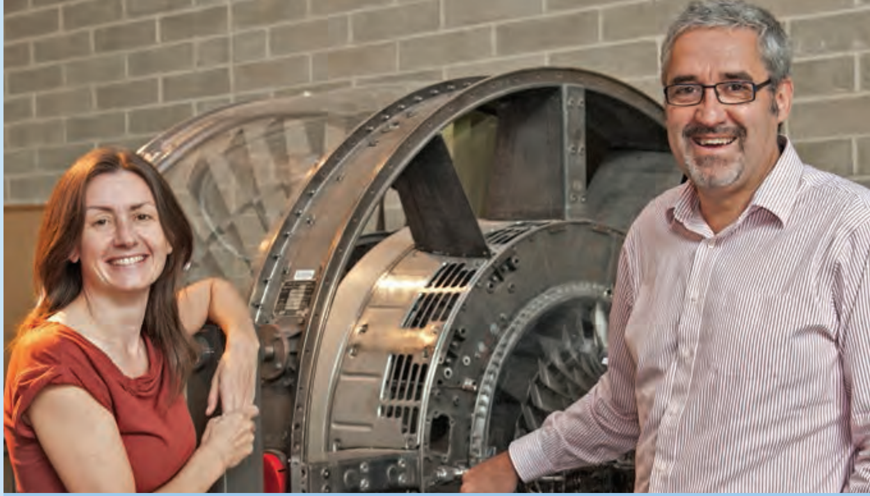
Despite ongoing challenges to the American and world economies, the future is bright; opportunities abound for aerospace and for AeroAstro. Certainly our students anticipate good things happening in the field; enrollment in our undergraduate program remains strong with 70 sophomores matriculating in the fall of 2013 — excellent news for a sector facing the wholesale retirement of an aging workforce. When you read Aerospace Industries Association president and chief executive officer Marion Blakey's article, written expressly for *AeroAstro*, on page 1, you'll learn more about the vital and robust role aerospace plays in innovation, economic development, and world security.

Here at MIT, we share Blakey's confidence in the future of the industry. AeroAstro research funding has risen by 55 percent over the past three years; there are more than 175 research projects in our labs and centers representing more than $30 million in expenditures by the DoD, NASA, other federal agencies and departments, and the aerospace industry.

During the last year, the department faculty committed to review and update our strategic plan, with the objective of developing a guiding strategy — a strategic initiative — for the upcoming decade. As part of this exercise, we conducted more than 60 interviews with aerospace leaders in industry, government, and academia. We reached out to our alumni, soliciting their views about aerospace and the direction the department should take in coming years. Professor Steven Barrett examines these interviews in an article starting on page 7.

Following the interviews and other groundwork, faculty gathered for a two-day strategic planning retreat in late January where we examined the state of the department and data gathered in advance of our summit. While there was consensus that the majority of our activities are aimed in the right direction, we recognized that there are exciting strategic opportunities, particularly in the areas of air transportation, autonomous aerospace systems, small satellites, and engineering education. All areas well match to our strengths, and in coming months as we flesh out and implement actions to embrace these opportunities, we anticipate our efforts will meet with great success. As always, we will be approaching these challenges by building on the individual strengths of our faculty and by collaborating with our colleagues inside and outside MIT.

It's an exciting time to be crafting a strategic initiative that includes prioritizing advancing engineering education. To this end, our planning identified two specific opportunities: first, to take a leadership role at MIT in engineering education and pedagogy, and second, to leverage the online educational MITx/edX initiative and become the worldwide leader in MOOC (the vernacular for massive open online course) aerospace education. As many of you know, in 2012 MIT and Harvard created edX, which we use as



the platform for online MITx courses. MITx will offer its first two AeroAstro courses in the fall of 2013: 16.101x Introduction to Aerodynamics, and 16.110x Flight Vehicle Aerodynamics.

Whether online or in the classroom, AeroAstro faculty are passionate about advancing engineering education. During the past two years, we conducted two pilot projects to assess the value of modularization (allowing students to mix and match elective classes) coupled with online technology in promoting new, more flexible, and more effective pedagogies. You'll read about these experiments in an article by several of our faculty that begins on page 33.

In recent months, the department co-hosted the 9th International CDIO Conference. Thirteen years since the CDIO (Conceive-Design-Implement-Operate)-based curriculum was pioneered in the AeroAstro Department, it is very satisfying to see the positive impact that CDIO has had not only in our department but in the in nearly 100 institutions around the world that have adopted our CDIO education model. For more about CDIO, visit http://www.cdio.org.

Like the rest of the Institute, the department is struggling with years of deferred facility maintenance. To that end, we are seeking support to renovate and upgrade several of our buildings, including our iconic and invaluable Wright Brothers Wind Tunnel, which celebrated its 75th anniversary this past summer. If you're interested in our plans for rehabing AeroAstro's buildings and facilities, please let us know. We'd be pleased to share our ideas.

As always, we invite you to get in touch with us and participate in our efforts and activities, be it by phone, email, or visit. Come see the changing face of AeroAstro and the MIT campus. Stay connected!

JAIME PERAIRE, Department Head

KAREN WILLCOX, Associate Head

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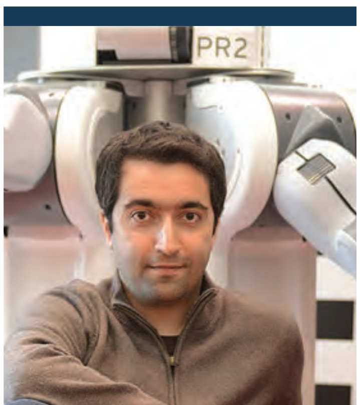

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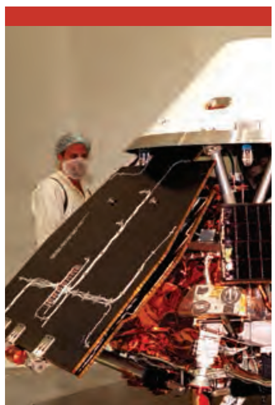

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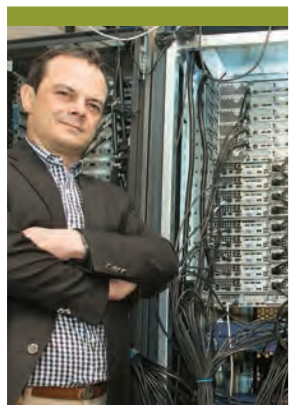

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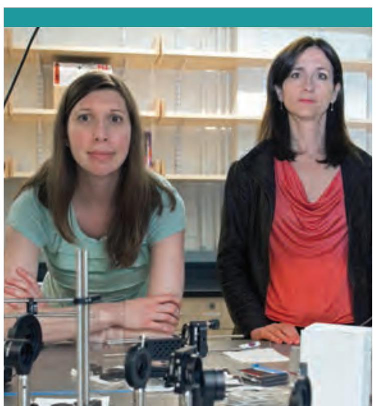

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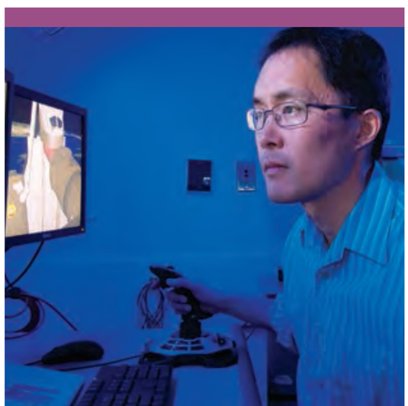

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Aerospace sales for 2012 were $218 billion, with strong orders for civil aircraft accounting for much of the 3.4 percent in sales growth over 2011. (William Litant)

GUEST COLUMN

America's aerospace and defense industry: a vital contributor to innovation, economic growth and world security

By Marion C. Blakey, CEO, Aerospace Industries Association

At the tail end of World War II, President Franklin Roosevelt commissioned Vannevar Bush, the brilliant former dean of MIT's School of Engineering, to study how the lessons of America's wartime mobilization of scientific expertise could be applied to society in peacetime.

Bush's 1945 report, *Science: The Endless Frontier*, remains today a classic examination of how America's scientific and technological enterprise — through cooperation between government, industry and university researchers — can be harnessed to advance technological innovation, economic growth and the security and well being of our people.

"The government should accept new responsibilities for promoting the flow of new scientific knowledge and the development of scientific talent in our youth," wrote Bush in his report. "These responsibilities are the proper concern of the government, for they may vitally affect our health, our jobs, and our national security. It is in keeping also with basic U.S. policy that the government should foster the opening of new frontiers and this is the modern way to do it. For many years the government has wisely supported research and the benefits have been great. The time has come when such support should be extended to other fields."

Today, the modern American aerospace and defense industry is very much a product of Bush's vision — and appropriately Raytheon, one of our leading member companies, was founded as the American Appliance Company by Bush and two other Cambridge-based scientists in 1922.

The member companies of the Aerospace Industries Association, the leading association for the industry, are at the forefront of developing disruptive technologies such as unmanned aircraft systems, of commercializing space transportation to low Earth orbit, of making our national air transportation system safer and more efficient, and of providing our war fighters with the sophisticated equipment necessary to successfully carry out military operations with reduced casualties. Fittingly, our association's board of governors is led by an MIT-trained electrical engineer named Bush: Wes Bush, the chairman, CEO, and president of Northrop Grumman.

BRIGHT SPOT FOR INDUSTRY, TRADE

Our association's fundamental premise is that American leadership in aerospace and defense is hard won, and we should not give it up easily. The U.S. aerospace and defense industry employs more than one million highly skilled workers. Additionally, a Deloitte study estimates the federal government employs 845,000 aerospace and defense workers at armed forces maintenance and repair depots, NASA, the FAA, other defense agencies including DARPA, and civilians working at the Department of Defense. Total aerospace sales for 2012 were $218 billion, with strong orders for civil aircraft accounting for much of the 3.4 percent in sales growth over 2011. A bright spot for our industry and the U.S. balance of trade are exports, up 16.5 percent in 2012 to $99.4 billion.

A bright spot for our industry and the U.S. balance of trade is exports, up 16.5 percent in 2012 to $99.4 billion.

Despite these positive indicators, our industry is gravely concerned about the impact that the massive, indiscriminate sequestration budget cuts will have on innovation, national security, the defense industrial base, other important government programs that have a major aerospace component, and our economy, with more than million jobs at risk.

Sequestration adds $500 billion in cuts over a nine-year period to the $487 billion the Budget Control Act of 2011 took from DOD budgets. Everyone from the president to the Joint Chiefs of Staff have said this level of cuts will undermine readiness and troop morale, create havoc for thousands of dedicated civil servants and companies throughout the defense industrial base supply chain, diminish R&D on new systems, and render our long-term defense strategy unexecutable.

There is great optimism that export market growth for American built jet aircraft, like Boeing's 787 Dreamliner, will further strengthen the aerospace industry in coming years. (Boeing)

There's also a significant domestic component to the sequestration story. An AIA-commissioned study by Econsult Corp. demonstrates that sequestration will force the FAA to make painful cuts to implementation of the NextGen air transportation system, leading to more gridlock in the skies, with the potential for ticket prices and cargo rates to rise substantially. We also worry that sequestration will lead to unacceptable delays to NASA's human exploration and science programs and to NOAA's development of next generation polar-orbiting weather satellites, the eyes in the sky that we depend on for life-saving forecasts. And we've argued that sequestration will force federal agencies involved in everything from agriculture, aviation, defense, energy, health, space and transportation to cut back on the research funding that leads to breakthrough innovations — exactly the wrong approach to positioning our nation to compete in the global marketplace.

Through our Second to None public education campaign, AIA has been fighting for an end to sequestration and to replace it with a balanced, bipartisan budget deal that would address our nation's debt and deficit problems through a combination of smart budget cuts and entitlement and tax reforms.

SEEKING NEW MARKETS

Regardless of the path forward our elected leaders choose, we recognize that in the existing fiscal environment our aerospace and defense companies must aggressively seek out new markets for our products and services in order to remain healthy. To begin, export growth can be an even larger contributor to the strength of our industry in the years ahead. In the past decade, for example, U.S. manufacturers such as Boeing have produced state-of-the art new technologies such as the fuel-efficient composite based 787 Dreamliner. With China building 70 new airports in

U.S. Munitions List export controls of unmanned aerial systems are hindering a huge potential U.S. advantage in a market that promises spectacular growth and great career opportunities for MIT graduates. (U.S. Marines)

the next three years, with India also committing to major airport expansion and Brazil preparing to welcome millions of visitors for the 2014 World Cup and 2016 Summer Olympics, there is great optimism that market demand for American built jet aircraft will increase in the years ahead.

On another export-related front, the Obama administration deserves real credit for its commitment to reforming our nation's outdated and counterproductive export control regime. Under new legislation, sales of commercial satellites and satellite components will no longer be tightly controlled by the U.S. Munitions List, making it easier for our companies to sell these products abroad. The U.S. share of global satellite manufacturing revenue fell from nearly 65 percent in 1999 to around 30 percent following the blanket imposition of military export controls on satellites, even if they didn't have a military purpose. Satellite export reform will stop what some experts have called a "Space Marshall Plan" that has created a rich market opportunity for other nations' industries by hobbling American companies in the competitive commercial marketplace. Similarly, the president initiated in March the process of moving parts and components for military aircraft and military engines off the USML, another victory for our manufacturers. The administration is now moving forward to review how a wide variety of aerospace and defense related products should be rationally controlled in ways that advance the long-term security and economic interests of the nation.

We hope that one area receiving special attention in the administration's export control review will be unmanned aircraft systems, that, along with smart phones and 3-D printing, Time Magazine labeled the three truly breakthrough technologies of the last decade. Currently, export control of UAS under the USML is hindering a huge potential U.S. advantage in a market that promises spectacular growth and great career opportunities for MIT graduates.

Of course, one UAS development receiving significant attention of late is the ongoing process to integrate them into the national airspace system as mandated by the 2012 FAA Modernization and Reform Act. Experts believe that we soon could have up to 30,000 UAS in the skies, with uses as varied as severe storm and wildfire monitoring, traffic management, law enforcement, border patrol and search and rescue. And as was the case with the rise of GPS technology, there are probably numerous UAS applications that people haven't even thought of yet. We recognize, however, that rapid technological developments can take a while to be fully accepted by society. The public's concern about UAS safety and privacy is valid, and must be adequately addressed before the full promise of this technological revolution can be realized.

SECOND TO NONE

Despite all the headwinds we face, America's aerospace and defense industry remains second to none precisely because we share Vannevar Bush's belief that America's progress depends upon our commitment to excellence in science and technology. We are confident in the future of our industry because we continue to attract bright young scientists and engineers. Careers in aerospace and defense offer opportunities found in no other industry to open up new frontiers of endless possibility.

MARION C. BLAKEY is president and CEO of the Aerospace Industries Association. Prior to assuming this position she served a five-year term as FAA administrator.

Surveyed AeroAstro alumni say the department should enhance its curriculum in the areas of business and entrepreneurship to equip graduates with the skills they will need in the aerospace industry of the future. Massachusetts-based company Terrafugia was founded in 2006 by alumni who are combining driving and flying in a series of unique vehicles such as the planned TF-6, a plug-in hybrid electric flying car. (Terrafugia)

THE FUTURE OF AEROSPACE

The MIT Course 16 alumni perspective

By Steven Barrett

In fall 2012, the Department of Aeronautics and Astronautics faculty set out to renew the department's strategic plan.

Our goal in this undertaking was, and continues to be, to make clear choices about the future that will affect the department's research and education enterprise over the next decade. Knowing that we don't exist in a vacuum (although we do have astronauts in our community), we needed advice about the forces shaping the aerospace sector over the coming decade. The question then — whom to ask?

We consulted with aerospace industry leaders. We talked to government officials. We interviewed National Academy of Engineering leaders. We quizzed one another. And, well aware that the biggest impact AeroAstro has on the world is through its alumni, we reached out to almost 2,000 of our graduates, more than 300 of who responded to our call. This article summarizes the results of this effort.

"Best education on the planet. Maybe on other planets, too, but I don't have the data to assess"

OUR ALUMNI

Our survey began by asking respondents to identify themselves by industry and employer. As one might expect, the number one industry in which our alumni work is aerospace. From their responses, it's clear that our graduates believe Course 16 has prepared them well for a wide range of technical and non-technical challenges — from solving deep research problems to architecting large-scale systems, and from designing products to leading organizational change. Those alumni not in aerospace work in healthcare, finance, government, the armed forces, and sustainable energy — to name but a few areas. Position titles and responsibilities include those of aerospace engineer, CEO, professor, pilot, chief scientist, physician, and consultant. Many of our alumni remarked that their education in Course 16, spanning the fundamentals of several engineering science disciplines to systems thinking and understanding the broader societal context, proved transferable to a range of career challenges.

> *"I have relied upon my education in the Department as the starting point for almost every problem I have been asked to solve — technical or otherwise throughout my career"*

THE CHALLENGES — PAST, PRESENT, AND FUTURE

The aerospace industry has faced, and will continue to face, major challenges. Our alumni have a deep understanding of these challenges, and in many cases have played a pivotal role in forging the future of the industry. We asked our alumni for their assessment of the major challenges for the industry over the past decade and over the coming decade.

The main challenge of the past decade cited by our alumni is that of government budget shrinkage and "politics and inconsistency." This has also been a period when aviation fuel costs and environmental impacts have come to the fore, motivated by both soaring energy costs and increasing environmental awareness. The large-scale complex systems challenges that are particularly acute in aerospace have come to dominate aerospace programs, resulting in spiraling and unpredictable costs.

Another challenge our alumni highlighted is that the aerospace workforce is aging. Engineering in general faces a STEM crisis, which is compounded by aerospace-specific factors including the rapid attrition of young recruits to the industry.

> *"Fluctuations in budget and poor opportunities for advancement … new engineers are going to continue to leave the industry"*

Most agree that all of these issues will only become more acute over the coming decade: government and defense funding, energy and environment, STEM and an aging workforce, and complex systems challenges being key concerns.

Our alumni foresee three major new challenges. First, that this will be the critical decade for commercial space flight — a period in which the sector may reach "escape velocity." This is seen as important given the budgetary uncertainty facing NASA. Second, the period may be one in which we see the widespread introduction of unmanned aerial vehicles into civilian airspace. Applications could range from security to environmental monitoring. Third, some of our alumni envision that the aerospace industry will have to become more commercially focused and more nimble to thrive in a "post-monolithic" era for aerospace.

AeroAstro alumni see us within a critical decade for commercial space flight — a period in which the sector may reach "escape velocity" in the form of vehicles like Blue Origins' orbital Space Vehicle. (Blue Origin)

"Defense and aerospace will become more commercially oriented ... to anticipate the market because the customer is moving away from funding specific products and solutions"

Alumni also noted that globalization and international competition will increasingly affect the U.S. defense industry. Few alumni cited specific technical challenges beyond the complexity of engineering systems as central to the last or next decade, but they did note that opportunities are likely to present themselves due to the prevalence of cloud computing, the rise of "big data" as a discipline, and the potential for UAVs in civilian airspace.

"An architectural paradigm shift is likely to occur in space programs from large monolithic spacecraft owned and operated by NASA ... to much more distributed architectures, potentially owned or operated by other partners"

AEROASTRO'S ROLE

We asked alumni to assess us with the benefit of hindsight and to suggest how AeroAstro can contribute to the future of aerospace. The dominant strengths highlighted were the quality of our faculty and students, the rigorous engineering training given to students, the systems thinking infused in the curriculum, and the research by, and reputation of, the department. Our sense of community and links to industry were also praised.

"Worldwide recognition of excellence, with potential for strong influence in politics, industry, and academia. Renowned faculty/staff with an admirable desire to teach. And a willingness to innovate and experiment with education"

Many of our alumni said we should enhance our curriculum in the areas of business and entrepreneurship to equip graduates with the skills they will need in the aerospace industry of the future. This is, perhaps, the continuation of a trend in aerospace engineering education. In the post-war period, the focus was on fundamental engineering sciences. This expanded to component design, then product design, and ultimately to systems thinking including the organizations within which complex aerospace systems are conceived, designed, implemented and operated. Alumni paint a future of aerospace that is more dynamic, distributed, and entrepreneurial than the large organizations and programs that have dominated aerospace through to the beginning of the 21st century, which our educational programs may need to both respond to and enable.

Beyond education, alumni see AeroAstro playing a leading role in UAVs, energy and the environment, and continuing to face the challenges of increasing complexity in aerospace systems. They also noted that we should continue to work closely with industry and deploy our influence in national policymaking.

"Course 16 can lead by tying industry to academia, and solving real-world problems that come directly from industry using state of the art research"

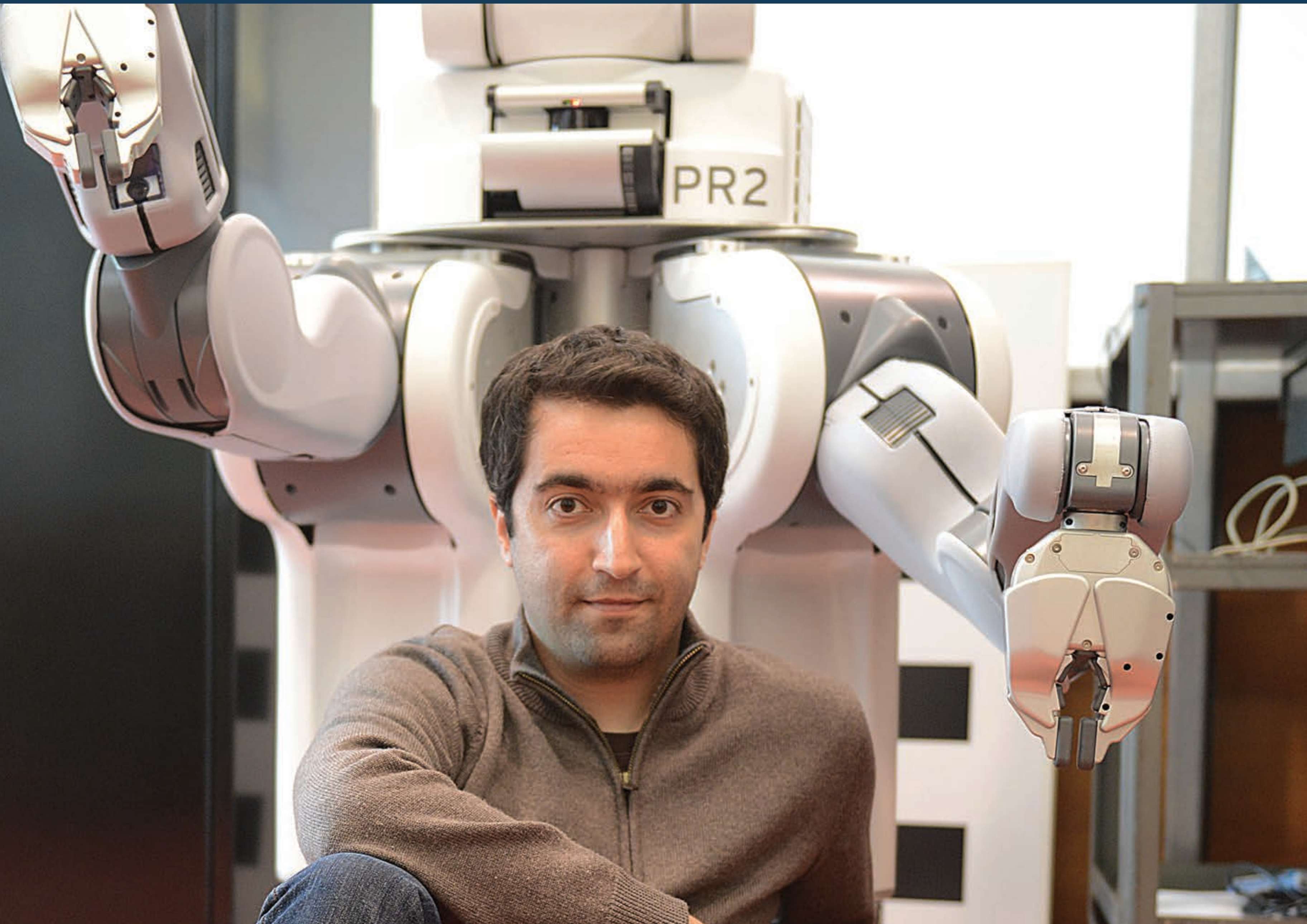
"Analyze policies and advocate for smart regulatory changes and investments"

CHALLENGES IN A CHANGING WORLD

Our alumni describe an industry facing enormous challenges in a fast changing world — one that will require the industry to change the way it does business, and yet continue to cope with the ever-increasing complexity of the aerospace products it develops and deploys. These challenges will not go away, and will be compounded with new challenges and new opportunities in commercial space flight, in UAVs, and a continuing fiscal tightening that will disproportionately affect aerospace. But they also describe an industry of immense opportunity and potential to change the world in connectivity, in security, and in sustainability. And they say we can make a difference.

"The next 10 years are going to define the path aerospace takes for a very long time. The engineers coming out of MIT can make a huge impact on this, and they need to be equipped to handle that responsibility"

STEVEN BARRETT is an assistant professor of aeronautics and astronautics. The goal of his research is to advance understanding of the air quality and climate impacts of aviation and other transportation emissions, and to develop technological, fuel-based and regulatory strategies to mitigate these impacts. He directs MIT's Laboratory for Aviation and the Environment (http://lae.mit.edu). Steven Barrett can be reached at sbarrett@mit.edu.



Professor Sertac Karaman with his lab's PR2 robot. The PR2, a commercially-available product, serves as a testbed for Karaman's research into making robots both more efficient and capable of working safely alongside humans. (William Litant)

Efficient motion: easy for us, a challenge for robots

By Sertac Karaman

Tasks that we humans consider simple or intuitive can be tremendously difficult for robots to perform.

Take the seemingly simple task of tidying up your living room after the dinner party. All you need to do is to move the dishes to the kitchen, place pillows that fell to the floor back on the couch, and put back the chairs near the dining table in an orderly fashion. That's it! As you go through this simple exercise, you walk around the room, use your arms to reach around, grab things, pick them up, place them elsewhere, often with a gentle touch. Without thinking, you move more than 30 joints in your body, all in perfect harmony. While doing so, your motion is efficient, especially in terms of your energy expenditure. You never exhibit the jerky roundabout motions that are often associated with robots.

Providing robots with that kind of efficient, natural, "human-like" motion is one of the long-standing challenges in robotics. Let me emphasize: the reasons for insisting on efficient robot motion go beyond aesthetics. In fact, natural motion is key to enabling robots to work alongside humans, as predictability of robots' motion is important if humans are to accept autonomous robots in their work and social environment. Efficiency of robot motion is central to many other emerging applications of autonomous systems, such as autonomous air vehicles, driverless cars, space exploration, nano-robotics, just to name a few.

CHALLENGES TO EFFICIENT MOTION

There are many challenges that stand before the ultimate goal of providing robots with efficient motion. An important element in this has to do with the actuation and sensing technology. Progress is still required in building powerful, fast, and precision actuation devices, and more so

The RRT* algorithm, when applied to his PR2 two-armed robot (shown here in a multiple-exposure image), helps the robot exhibit more human-like behavior. MIT has been home to several important experimental achievements for demonstrating sampling-based planning algorithms. One dates back to the Defense Advanced Research Projects Agency's Urban Challenge that took place in 2007. The Urban Challenge was a robot race-competition posed by DARPA to build a full-size autonomous car that can navigate in urban traffic with no human intervention. (Alejandro Perez)

in developing affordable and powerful sensors that can provide robots with an extended situational awareness. However, even with perfect sensing and actuation, there remains a key challenge: the analysis, design, and implementation of algorithms that can generate collision-free motion, coordinating many degrees of freedom in an efficient manner.

In fact, finding a collision-free path for a robot to reach a desired configuration, called "the motion planning problem," is a fundamental problem in robotics. This problem of navigating in a complex environment is embedded and essential in almost all robotics applications. Moreover, it has found several applications in a diverse set of fields that reach well outside the robotics domain including computational geometry, computer animation, and drug development.

Fascinated by far-reaching applications, many researchers have studied variants of the motion planning problem, at least since the emergence of algorithmic robotics, which dates back to late 1960s. However, the advent of the theory of computation quickly lead to computational hardness results: it was shown as early as 1979 that the motion planning problem is computationally extremely challenging when the number of degrees of freedom is more than five or six.

SAMPLING-BASED ALGORITHMS A POWERFUL TOOL SET

Despite these discouraging computational hardness results, the algorithmic robotics community put substantial effort into designing practical algorithms for motion planning. In particular, sampling-based algorithms emerged as a powerful set of tools tailored to address this problem. These algorithms randomly sample configurations and connect these configurations in some smart way to form a compact graph structure. It's often the case that a small number of samples are adequate to answer challenging motion planning queries, even for complex robots operating in cluttered spaces.

When proposed in the mid-1990s, sampling-based algorithms became the first algorithms to solve complex problem instances involving more than five degrees of freedom.

This idea of sampling has revolutionized the field of motion planning. When proposed in the mid-1990s, sampling-based algorithms became the first algorithms to solve complex problem instances involving more than five degrees of freedom. Since then, these algorithms have achieved tremendous experimental success. They were implemented to run on a variety of robotic platforms, and showcased in several major robotics events.

MIT has been home to several important experimental achievements for demonstrating sampling-based planning algorithms. One dates back to the Defense Advanced Research Projects Agency's Urban Challenge that took place in 2007. The Urban Challenge was a robot race-competition posed by DARPA to build a full-size autonomous car that can navigate in urban traffic with no human intervention. MIT's entry vehicle, a Range Rover-based vehicle we named Talos, was guided by a robust extension of a widely used sampling-based motion planning algorithm called the Rapidly-exploring Random Tree (RRT).

A FEASIBLE SOLUTION

Sampling-based algorithms, such as the RRT, are great at finding a feasible solution, one that reaches the desired configuration. However, if not carefully implemented, the "efficiency" of the trajectory is often very poor as it includes, for instance, zigzag paths due to random sampling. In fact, a large part of our effort in implementing the RRT algorithm on Talos was devoted to developing online methods that can improve the quality of the path returned by the algorithm.

Recently, we have been working on improving these algorithms to provide solutions that are close to optimal trajectories, for instance, those that with minimal path length. One of our recent contributions in this direction includes the RRT* (the asterisk is part of the name) algorithm. Compared with the RRT algorithm, the RRT* guarantees convergence to optimal solutions, which the RRT algorithm lacked. That is, when the RRT* algorithm is run for enough amount of time, it will return a trajectory that is arbitrary close to the optimal trajectory. Moreover, the extra computational overhead introduced by the RRT* algorithm is little when compared to the RRT algorithm.

The field inches a little closer every day toward singularity for robot motion, when robots will finally start to exhibit motion that is unquestionably better than what humans can do.

We have implemented the RRT* algorithm for a number of platforms including an autonomous forklift, a personal two-armed robot, and a simulated off-road racing car. In all these cases, the RRT* exhibits superior performance when compared to the baseline sampling-based algorithms. In particular, the solutions provided by the RRT* makes personal robots behavior more human-like and reproduces how an off-road racecar driver turns a tight corner.

During the last decade, many advances have revitalized algorithmic planning. Enabled by the recent advances in sensor, actuation, and computation technologies, the field inches a little closer every day toward the singularity for robot motion, when robots will finally start to exhibit motion that is unquestionably better than what humans can do.

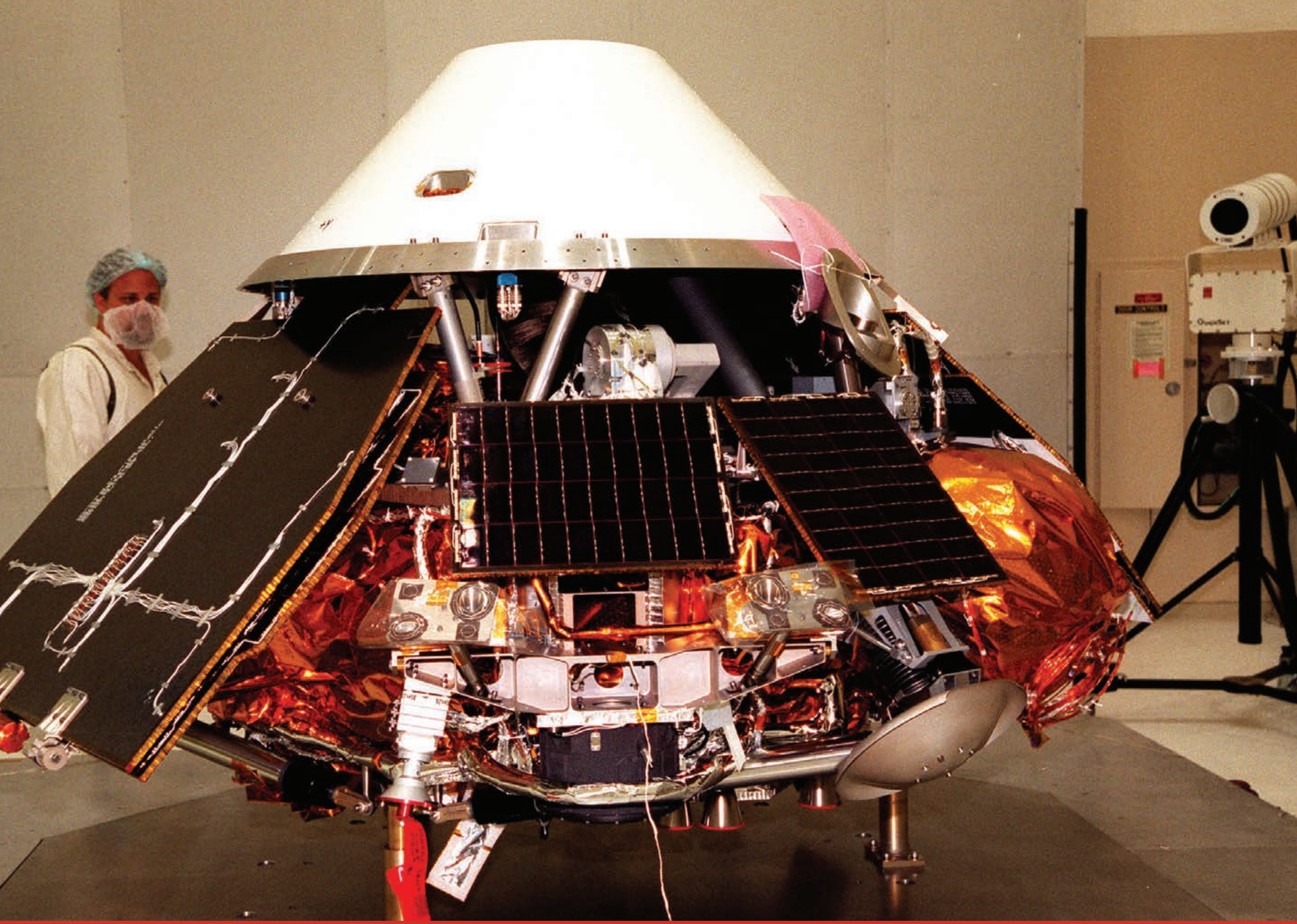
This author is incredibly excited to live in this time of renaissance for robot motion. Within the next two decades, expect advances in motion planning that parallel those achieved in artificial intelligence during the past couple of decades. Days that humanoid robots can dance alongside humans may be far ahead. But, just like computer artificial intelligence Deep Blue beat chess champion Garry Kasparov in 1997 and Watson bested its human Jeopardy opponents in 2011, expect full-size robotic race cars to drive faster and better than Formula One world champion Michael Schumacher and robotic airplanes to outmaneuver even the best human acrobatic pilots.

Talos, MIT's entry vehicle in the Defense Advanced Research Projects Agency's Urban Challenge, was guided by a robust extension of a widely used sampling-based motion planning algorithm called the Rapidly-exploring Random Tree. (Jason Dorfman)

POTENTIAL WIDE IMPACT

Planning algorithms also hold the potential for long-lasting societal and economic impact. Algorithms that predict drivers' intentions and react when necessary may save many lives that would otherwise be lost to traffic accidents. Other planning algorithms can keep tight air spaces safe, take more significant roles in governing unmanned vehicles, and help us discover our planet and beyond. We are in a good position to take a lead role and make MIT and the AeroAstro Department home to the development and deployment of this technology.

SERTAC KARAMAN is the Charles Stark Draper Assistant Professor of Aeronautics and Astronautics. His research interests lie in the broad areas of robotics and control theory. He studies the applications of probability theory, stochastic processes, stochastic geometry, formal methods, and optimization for the design and analysis of high-performance cyber-physical systems. Sertac Karaman may be reached at sertac@mit.edu.



The Mars Polar Lander, shown in the Spacecraft Assembly and Encapsulation Facility-2 prior to launch, is believed to have been destroyed when an improperly terminated engine firing caused the lander to impact the Martian surface at high velocity. (NASA)

TRADITIONAL SAFETY TECHNIQUES FALL SHORT FOR TODAY'S SYSTEMS

Accident prevention in a complex world

By Nancy Leveson

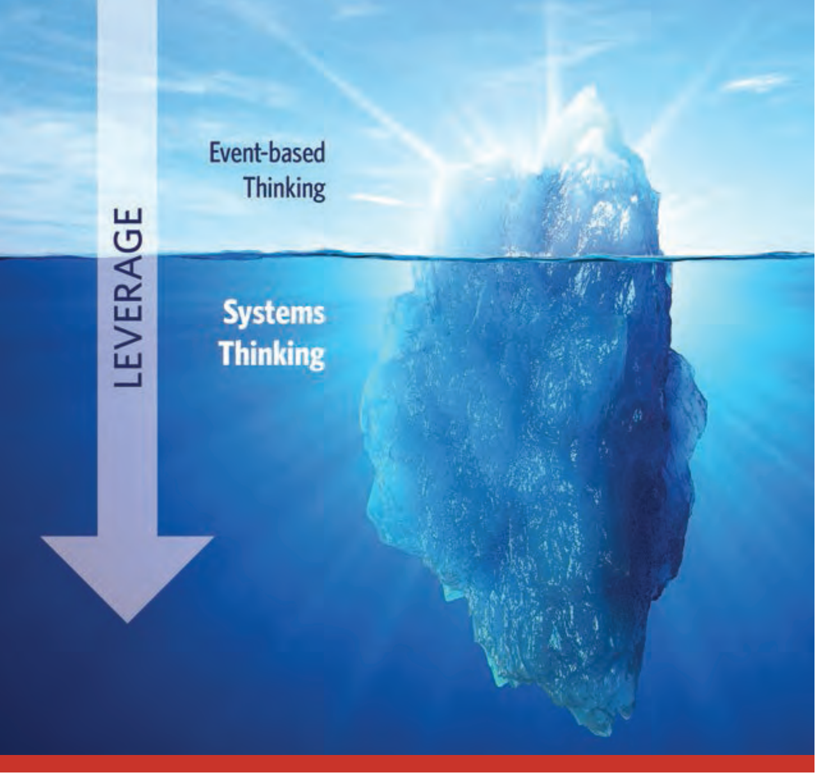
The increasingly complex systems we are building today enable us to accomplish tasks that were previously difficult or impossible. At the same time, this complexity and the new engineering technology that makes such complexity possible have changed the nature of accidents.

The traditional safety and reliability engineering techniques that are used today were created at least 50 years ago and are being challenged by the new engineering environment. They particularly fall short with respect to software and the new role operators play in complex systems.

In the Systems Engineering Research Lab, which I direct, we develop more powerful and cost-effective approaches to safety engineering and risk management that are better suited to today's complex, software-intensive systems and that incorporate considerations of the social and organizational world in which our systems are designed and operated. The new approaches start with a new, expanded model of accident causation. My students and I are creating new techniques and methodologies based on this model.

WHY DO ACCIDENTS OCCUR?

Traditionally, accidents have been assumed to result from chains of directly related single or multiple component failures. These failures are usually assumed to be random. The standard solution is to prevent such component failures or to build a fail-safe system where individual component failures do not lead to an accident. Fault tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) are widely used analysis techniques based on this model. While they can identify the potential for accidents resulting from individual component failure, they



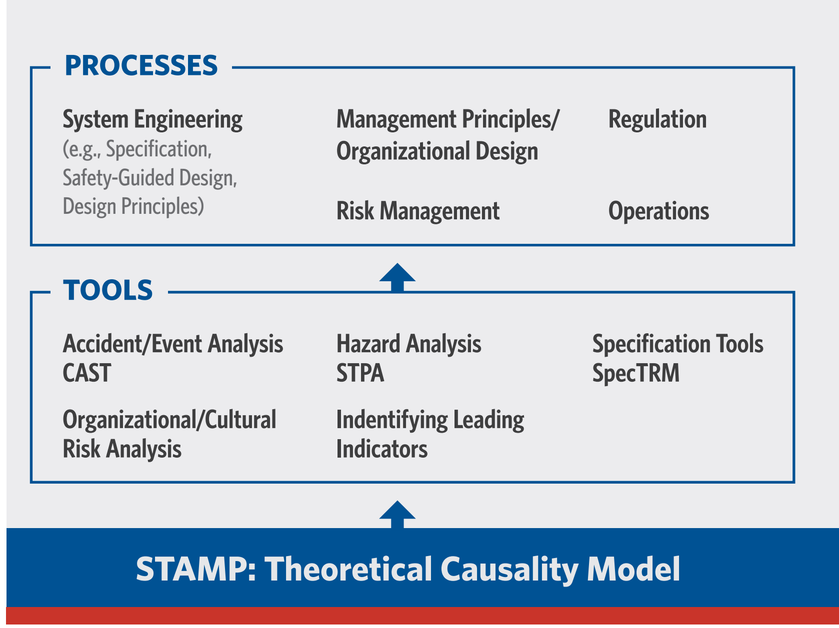
The use of Systems Thinking provides much more leverage in understanding and preventing accidents than do traditional event-based approaches (William Young graphic, Shutterstock image)

omit losses resulting from interactions among system components that have not failed but satisfy their specifications (which were inadequate). For example, in the 1999 Mars Polar Lander mishap where it is believed an improper descent engine shutdown caused the spacecraft to impact the planet surface at high velocity, each of the spacecraft components met their requirements specifications: The fault lay in system engineering and in the incomplete and incorrect understanding of the required behavior of the spacecraft components. Similar system design inadequacies have resulted in other catastrophic spacecraft and aircraft losses.

Software and flawed software requirements often play a role in these *component interaction accidents*. The role of software should not be surprising: Software usually embodies system design and functions formerly implemented by electro-mechanical components. The older electro-mechanical systems were simple enough that they could be exhaustively tested before use, thus identifying system design errors and leaving primarily component failures to be dealt with during system operation. Software-intensive systems cannot be thoroughly tested, however, and the system design errors that are missed can lead to serious losses. We use software so that we can increase complexity but, at the same time, we are building systems in which all the potential interactions among components cannot be thoroughly planned, understood, anticipated, and guarded against.

To deal with these limitations, a new, more powerful model of accident causation is needed. System-Theoretic Accident Model and Processes (STAMP) expands the old failure model of accident causation to include the new accident causes we are experiencing today. It is based on systems theory and systems thinking rather than reliability theory and assumes accidents are caused by inadequate enforcement of safety constraints on the component and system behavior. Examples of such constraints: two aircraft violate minimum separation requirements, heat is inadequately controlled in lithium-ion batteries, the software inadequately controls the descent speed of the Mars Polar Lander, an O-ring does not prevent the release of gas from a Space Shuttle field joint.

STAMP effectively redefines the safety problem as a *control* problem rather than simply a reliability problem. Preventing component failures is still part of the solution, but the overall design goal is not just to reduce component failures but, more generally, to enforce behavioral constraints on the components and the system as a whole.



Potential uses for System-Theoretic Accident Model and Processes (STAMP)

REVOLUTIONIZING SAFETY ENGINEERING

Applying STAMP opens up a large number of exciting possibilities for safety engineering and risk management in complex systems.

STAMP is just a theoretical model, it is not a tool itself. But it provides the basis for constructing new, more powerful tools and then using those tools in greatly improved processes.

Causal Analysis based on Systems Theory (CAST) is a structured, more comprehensive mishap analysis technique. It assists in looking beyond “operator error” and “component failure” as the cause of accidents and understanding *why* these errors and failures occurred, including the system design, organizational, social, and managerial factors that contributed to the component failures, erroneous actions, and flawed decision making. CAST has been used on dozens of accidents and incidents in aviation, chemical plant, railway, air traffic control, medical device, space, and other systems. All the CAST analyses to date have identified more causal factors than the official accident reports.

US Coast Guard Commander Jon Hickey, for example, applied CAST to investigate a spate of recent Coast Guard aviation training accidents. The standard accident analysis techniques used did not find common systemic factors in these accidents, but CAST did. Paul Nelson, a Comair pilot, used CAST to identify many factors that contributed to, and helped explain, the 2006 Comair crash in Lexington, Kentucky, that had not been identified in the NTSB report. The Dutch Safety Agency is using CAST to investigate aircraft, railroad, and traffic accidents as well as child abuse, medical errors, airport runway incursions, and other incidents.

Many newly identified mishap scenarios involved components operating exactly as intended: the complexity of their interactions led to unanticipated system behavior.

System Theoretic Process Analysis (STPA) is a new, more powerful hazard analysis technique based on STAMP. It uses basic control theory approaches to identify hazard causes and to generate system and component safety requirements. STPA is being used in industry and universities on a large variety of systems including spacecraft, aircraft, medical devices, automobiles, railroads, nuclear power, and defense systems. In all cases, STPA found the potential accident scenarios identified by engineers using Fault Tree Analysis and Failure Modes and Effects Analysis, but it also found important paths to mishaps that these traditional analysis techniques did not — and could not — identify.

In space, for example, JAXA (the Japanese Aerospace Exploration Agency) evaluated STPA by using it on the H-II Transfer Vehicle unmanned space cargo transport to the International Space Station and found more potential paths to a loss than identified in the fault tree created for NASA. They are now using it on a new joint NASA/JAXA scientific satellite and in the early architectural tradeoff analysis for JAXA's manned crew return vehicle.

In defense, the deployment and field testing of the U.S. ballistic missile system was delayed for six months to fix all the paths to inadvertent launch found by using STPA that had not previously been identified. While component failures were identified in this effort, many of the newly identified mishap scenarios involved components operating exactly as intended: the complexity of their interactions led to unanticipated system behavior. Examples include missing cases in software requirements and timing problems in sending and receiving messages. As an example

The Japanese Aerospace Exploration Agency evaluated System Theoretic Process Analysis on the H-II Transfer Vehicle unmanned space cargo transport, seen here in an artist's conception docking with the International Space Station. They found more potential paths to a loss than identified in the fault tree created for NASA. (NASA)

of the latter, message A may have been sent before message B, but message B might be received before message A, resulting in unexpected system behavior. Such problems cannot be identified by the traditional failure-oriented analysis methods.

We also have applied STPA to new NextGen air traffic control upgrades and found more hazardous scenarios than identified by the fault tree/event tree mix being used on these systems. NextGen is the set of changes planned to take advantage of new technology such as satellite communication to increase throughput and efficiency in our air transportation system.

In an MIT master's thesis, Vincent Balgos analyzed a blood gas analyzer that had been recalled by the FDA because of a potentially fatal incident. This medical device had previously been evaluated using FMEA, which found 75 scenarios to a mishap. STPA, in contrast, found 175 scenarios and took much less time and effort (weeks as opposed to months). Only STPA found the scenario that led to the recall, and, in fact, found nine scenarios leading to it.

Other examples include evaluations and comparisons of STPA and traditional hazard analysis techniques on a nuclear power plant design, a proton radiation medical therapy device, and air traffic control incidents. In all cases, STPA found more paths to losses.

STPA has also been applied in many cases without an explicit comparison to traditional techniques including a Medtronic artifical pancreas; a nuclear power plant safety system; CO_2 capture, transport, and storage; a large oil and gas engineering project, automotive problems, including unintended acceleration; a home surveillance robot; integrated modular avionics (for interoperability and change analysis); and hydropower and dam safety, among others.

One of the most surprising results of these uses on real systems is that not only is STPA more powerful than current hazard analysis techniques, but it also appears to be easier to use.

One of the most surprising results of these uses on real systems is that not only is STPA more powerful than current hazard analysis techniques, but it also appears to be easier to use, according to the feedback we are getting, and requires fewer resources. STAMP and systems thinking may provide a more cost-effective way to manage system safety and risk.

People are also trying STPA on general risk management problems beyond classic safety problems, including risk analysis in engineering project development and risk analysis of workflow and procedures used in hospital radiation therapy. New projects we are starting include integrating sophisticated human factors design into hazard analysis, analyzing US Air Force flight test operations, and identifying leading indicators of increasing risk in complex operational projects. We and others are even looking at the application of STPA and CAST to the financial world and to security, cyber-warfare, and occupational safety.

While many of the current uses of STPA are on existing designs and systems, it should ideally be embedded in the top-down systems engineering process so that safety is built into the system design from the beginning. Additional costs for safety engineering (which often are the result of late project rework efforts) can be totally eliminated, or at least minimized, if safety analysis is used to guide engineering decision making from the beginning. We have also created some general principles for designing to reduce human (operator) errors and have further work planned on this topic as well as how to safely manage and operate safety-critical systems.

A recent three-day workshop at MIT on STAMP attracted more than 200 participants from 18 countries, most of whom had already tried or are using STAMP-based tools. A counterpart European conference on STAMP was held in Germany in May 2013.

In order to improve the success of our engineering endeavors we need to go beyond the techniques and processes created decades ago for much simpler systems than we are building today. These approaches are not powerful enough to handle the increased complexity and new technology, particularly software and digital systems, being incorporated into today's systems. Systems thinking is needed to increase the probability of successfully achieving our mission goals and to reduce accidents and losses in the process.

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Professor Raúl Radovitzky is researching high-fidelity computer modeling and simulation that will enhance material failure predictions. (William Litant)

Understanding and preventing materials failure

By Raúl Radovitzky and Andrew Seagraves

Device and system reliability is often determined by the failure response of the material systems involved.

This is particularly relevant in situations involving extreme dynamic loading environments: whether it is the hundreds of micrometeorite impacts the Hubble telescope receives every year, a flock of birds or a piece of tire sucked into a jet engine fan, or an impact-damaged reinforced carbon-carbon heat shield tile expected to protect an atmosphere entry vehicle, we aerospace engineers constantly worry about material and structural failure.

We must try to understand how damage nucleates and propagates within materials; for example, upon impact loading, a complex process which can only be pursued via high-fidelity computer modeling and simulation (M&S). The expected role of M&S is to provide mechanistic explanations of the physics involved, which can help in the assessment and optimization of system damage vulnerability in operating as well as under unexpected loading conditions. Yet the accurate modeling of dynamic fracture remains one of the most difficult challenges in computational mechanics.

Accurate modeling of dynamic fracture remains one of the most difficult challenges in computational mechanics.

Take, for example, the tragic Columbia accident. Perhaps the main culprit in the decision to return the shuttle to earth was the later-to-be-found incorrect simulation-based assessment of the damage sustained by the heat-shield tiles during blastoff. As it turned out, the simulation tool employed was unable to describe the impact fracture mechanisms of the

Damage to a Space Shuttle Endeavour tile where it was struck by a piece of foam from the external tank during the STS-118 launch on August 8, 2007. (NASA)

reinforced carbon-carbon tiles, leading to incorrect, under-conservative predictions. The main reason modeling material damage and failure is so challenging is that solid materials subject to extreme loads exhibit intricate three-dimensional patterns of fracture. So far there have been no successful approaches for simulating this type of problems due to the lack of algorithms which at the same time incorporate sound mechanics of fracture as well as the requisite exceedingly-high resolution to capture the complex three-dimensional crack patterns.

SIMULATION BREAKTHROUGH

Our research group has recently made an important breakthrough toward this end: we have proposed the first scalable algorithm for the large-scale simulation of dynamic fracture of brittle solids. This algorithm has furnished the first extreme-scale simulation and systematic study of complex fracture and fragmentation in three dimensions.

Orbital debris impact damage to the Hubble Space telescope. (NASA)

The method is based on a class of computational methods for modeling partial differential equations known as discontinuous Galerkin formulations. (Galerkin methods are a means for converting a continuous operator problem, such as a differential equation, to a discrete problem.) Material fracture is modeled using so-called cohesive theories of fracture. Among the unique characteristics of the new algorithm enabling these types of simulations are the ability to describe sharp cracks as discontinuities in the solid material and to track their evolution based on true fracture mechanics models, and the ability to produce exceedingly-large computational models that can be generated in a distributed and scalable manner on massively parallel computers with tens of thousands of processors.

One of the key pass-fail tests in dynamic fracture mechanics is whether the models can accurately capture the speed and extent of crack propagation under different load intensities.

With full machine access to Department of Defense Supercomputing Resource Center supercomputer, we demonstrated the strong and weak scalability of the computational framework on up to 17,264 processors and for problem sizes up to 19.3 billion degrees of freedom.

One of the key pass-fail tests in dynamic fracture mechanics is whether the models can accurately capture the speed and extent of crack propagation under different load intensities. We have therefore put significant effort in validating our computational framework against experimental

On January 15, 2009, USAir Airbus A320-214 struck a flock of Canada Geese during its initial climb out, lost engine power, and ditched in the Hudson River off midtown Manhattan. The accident is another example of a catastrophic situation resulting from extreme dynamic loading. (Wikimedia)

data. Specifically, excellent agreement was found between predicted and measured crack speeds and their dependence on impact velocity in edge-on impact fracture tests.

We have used the validated tool to study fracture patterns arising in ceramic plate impact. This is key in the design of protective material systems including personal armor, where the localization of damage in a limited set of fracture planes severely reduces the ability of the material to dissipate energy while the fracture surfaces provide kinematic mechanisms which enable the incoming threat to defeat the armor system. Complex patterns of conical, radial and ring cracks observed in experiments, which have thus far remained elusive to computational modeling, were naturally captured by our simulations. The algorithm has also captured for the first time the transition between ring and edge cracks observed experimentally in the impact of thin brittle plates.

MILITARY BALLISTIC PROTECTION

The software platform SUMMIT where this algorithm has been implemented is currently assisting colleagues at various Army organizations (the Army Research Laboratory, Tank Automotive Research Development and Engineering Center, Program Executive Office Soldier and Natick Soldier Research Development and Engineering Center) in the assessment of novel protection material systems and improved strategies for ballistic protection. Army Research Office funding through the MIT Institute for Soldier Nanotechnologies and the Office of Naval Research is supporting the work.

We are currently expanding the capabilities of the SUMMIT code in a number of directions, including further algorithm improvements employing high-order field interpolation methods for improved accuracy in the description of stress waves; and a multiphysics capability to simulate the complex coupled hydraulic poromechanics fracturing in non-conventional gas and oil reservoirs to assist in operations planning with reduced environmental impact.

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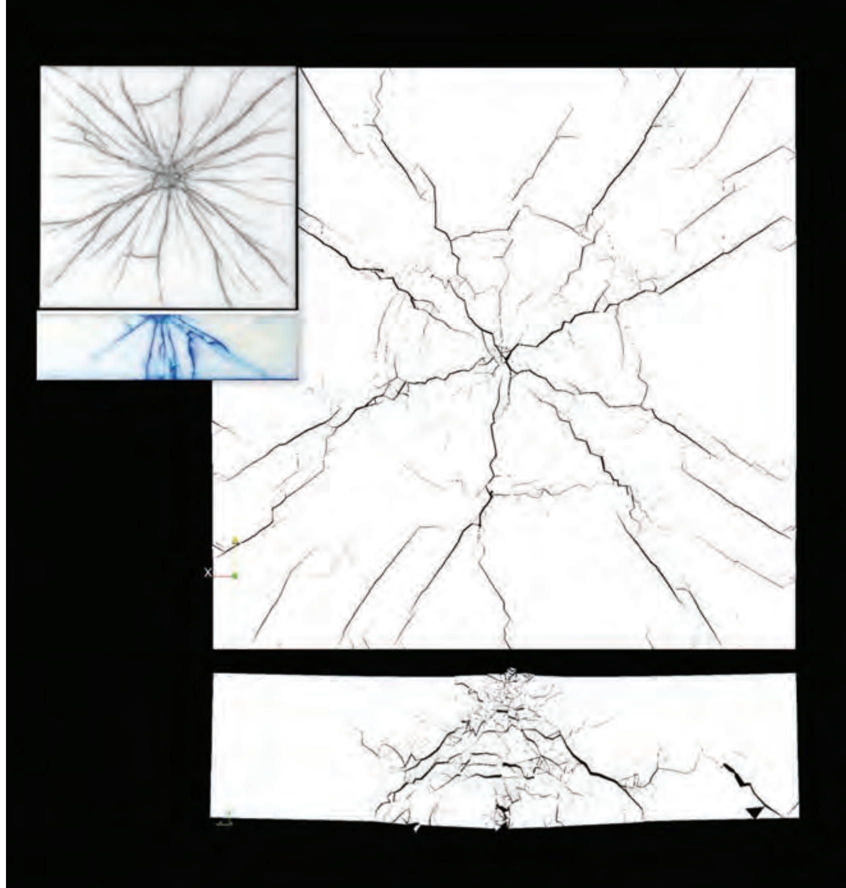


Impact conical and radial crack patterns in brittle plates (left) and the first computer simulations capturing these complex fracture mechanisms.

Professor Qiqi Wang directs Computational Methods in Aerospace Engineering (16.90) students in a role-playing exercise simulating behavior of a differential equation that produces a shockwave, AeroAstro is teaching the course using an “inverted classroom” style that requires the students to learn the material prior to lectures, which enhances their understanding through problem solving and interactive activities like this one. (William Litant)

Promoting independent study in the AeroAstro junior year

By David Darmofal, Raul Radovitzky, Glenda Stump, QiQi Wang, and Karen Willcox

The MIT Aeronautics and Astronautics Department is experiencing a growing interest in creating more flexibility in our curriculum.

The 2011-2012 *AeroAstro* issue (http://bit.ly/11dS2EY) reported on our new 16-ENG flexible degree, which offers Course 16 students the opportunity to combine an aerospace engineering core with a six-subject concentration in an area of their choice. 16-ENG has continued to grow in popularity since its launch in 2010. The push towards flexibility comes at a time when educational technologies and strategies for online learning are at the forefront of the conversation around MIT and around the world. In this article, we'll take a look at an exciting educational experiment carried out in the department that aims to use online learning strategies to move us to a more flexible pedagogical model.

MOTIVATING A FLEXIBLE CURRICULUM

What are the motivations for pursuing such a model? One is a desire to enable AeroAstro students to participate in the "semester-from anywhere" — a concept promoted by the Dean of Engineering enabling students to spend up to a year off campus participating in enriching educational opportunities (e.g., industrial internships, visits to other academic institutions, projects in the developing world) without significantly interrupting their MIT education. Another is the prospect of using online technology as a way to achieve active learning and greater levels of student-faculty interaction in the on-campus classroom. And another motivation is the benefit in curriculum flexibility offered by modularizing some of our classes, potentially allowing students to "mix and match" their elective subjects to a greater degree in the future.

In the fall of 2011, under funding from the School of Engineering and the MIT Council on Educational Technology, an AeroAstro team comprising professors Dave Darmofal, Raul Radovitzky, QiQi Wang, and Karen Willcox; research scientist Douglas Allaire; postdocs Laslo Diosady, Martin Hautefeuille, Aurelie Jean, and Adrian Rosolen; and PhD student Chad Lieberman launched an educational experiment in two AeroAstro Professional Area Subjects: 16.20 (Structural Mechanics) and 16.90 (Computational Methods in Aerospace Engineering). The experiment assessed two hypotheses:

Exercises were designed to help guide self-study by providing immediate feedback to students, and provide faculty with information to tailor class interactions around the material where students' results showed an inconsistent or incomplete understanding.

(H1) It is possible to create a modularized semester where student learning is equal to or better than the traditional approach and in-depth experiences are made easier.

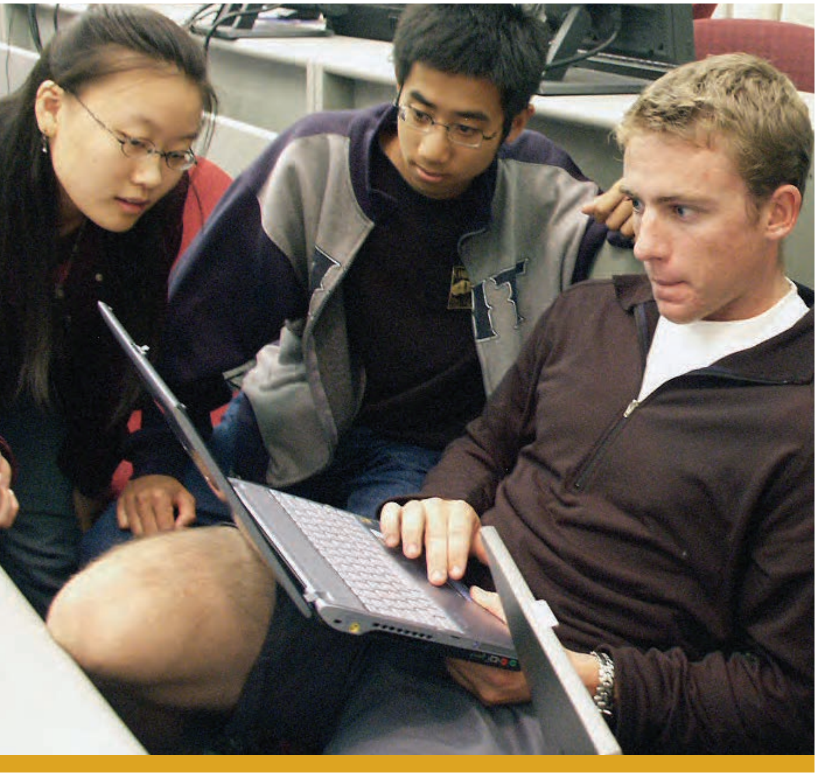
(H2) A learning model emphasizing active student-instructor engagement coupled with independent student preparation can be effective for achieving subject learning objectives for students both on-campus and off-campus.

Preparation for the experiment included designing a modularized curriculum for each class, creating an online/in-class integrated learning strategy, finding simple low-cost ways to enable remote student participation, and creating a detailed evaluation plan.

Both classes used the "flipped classroom" model. Ahead of class, students were required to complete self-study or "look-ahead" modules of online material, which included lecture notes, video snippets, and an online discussion forum. Then in class, the traditional lectures were replaced with active learning sessions, which involved collaborative problem-solving, programming assignments, and mini-lectures. These sessions were web broadcast (using WebEx and Adobe Connect) and recorded for later playback. In 16.90, the online material included embedded exercises — multichoice and short answer questions, as well as simple Matlab coding exercises. These embedded exercises were designed to help guide students' self-study by providing immediate feedback (via automated grading), and to provide faculty with information to tailor class interactions around the material where students' results showed an inconsistent or incomplete understanding of key concepts.

AeroAstro's experiments are designed to see if those participating in MIT's on-campus educational experience can benefit from elements of online education delivery. (William Litant)

Class sessions in 16.20 consisted of table discussions of read-ahead materials and in-class solution of assigned problems in groups of five to six students per instructor. Students connecting remotely (typically 5-10 out of 27) joined the discussions at a specific table via Skype and desktop sharing. Active participation in class amounted to as much as 20% of the total course grade. For 16.90, class sessions included demonstrations or mini-lectures exploring concepts introduced in the "look-ahead" material, concept questions targeting areas of common misconceptions, short problem-solving sessions to strengthen student ability to apply numerical analysis techniques, and program sessions in which students were led through the implementation of numerical methods applied to aerospace-motivated problems.



Course 16.90 is using the beta version of the edX Studio platform — the platform used to deliver MITx online classes. AeroAstro faculty are optimistic that this trial will show the benefits of MITx to MIT residential-based education. (William Litant)

EVALUATING ACHIEVEMENT, ATTITUDE

The evaluation plan was created in collaboration with the MIT Teaching and Learning Lab. We analyzed student achievement of learning objectives through the embedded exercises, problem sets, exams, and projects. This analysis included comparisons of student achievement data from previous semesters. We also evaluated student attitudes through "muddiest point" cards (where students reflect on the lecture and write down the point they found the muddiest and need clarification about), student attitude/learning behaviors surveys, and student interviews.

The evaluation showed that, on average, students reported a positive attitude regarding whether the new format contributed to their learning. The students were mostly positive or neutral about whether they liked the new format better than a traditional format. Students made positive comments about online class notes with embedded questions and videos, and about interactive sessions that involved solving problems as a small group in class under the guidance of a TA or faculty member. Negative comments were made about some of the interactive sessions being mismatched with the students' grasp of the material and that some of the online notes required more explanation. Instructors noted that the interactive nature of the in-class sessions brought positive energy and excitement to the classroom, and served to bring the students together as a cohort. Professor Raul Radovitzky noted that, based on overall classroom climate, "this was the most fun class I've taught, both for students and instructors." Overall, while the student evaluations show that some improvements are needed, we are optimistic that the experiment was a success and that this pedagogical model is worth pursuing further.

In Spring 2013, both 16.20 and 16.90 continued to use the new pedagogical format. Both classes implemented improvements based on lessons learned last year, as well as continued to develop a richer repository of online content (including more video snippets). Another change is that 16.90 is using the beta version of the edX Studio platform, the platform used to deliver MITx classes. While designed with the MOOCs (massively online open courses) in mind, we are optimistic that the Studio software also provides an excellent platform for enriching MIT classes. We hope that our study will be one of the first to show the benefits of MITx to MIT residential-based education. Looking to the future, the department is reviewing options for applying this pedagogical model to other undergraduate classes in our curriculum.

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While most jet fuel today is derived from petroleum, feedstocks can also be derived from other fossil sources or biomass. These are then converted to drop-in jet fuels through different processes. (Shutterstock)

Fueling the future of flight

By Steven Barrett

Today's air transport system depends on having a plentiful, secure supply of liquid hydrocarbon fuel. These are typically kerosene-type jet fuels such as Jet A, Jet A-1 or JP- 8, which have a high energy density both by volume and mass.

Jet fuels must satisfy a number of important safety-related constraints including thermal stability (to avoid thermal deposits building up in hot components) and freezing point (given the low temperature at high altitude).

Jet fuels in use today are almost exclusively petroleum-derived. While petroleum-derived jet fuel has proven reliable and available at a cost that enables ever-greater sections of society to travel, it has two key disadvantages. First, combustion of fossil fuels results in net CO_2 emissions (just over 3 kg of CO_2 per kg of jet fuel burned directly, and more if indirect emissions associated with production and refining are considered). CO_2 is the primary greenhouse gas, although others are significant too. Additionally, other emissions including SO_x, NO_x, and particulate matter are a risk to human health and affect the climate. Second, energy security and independence is an increasing concern for a number of countries. This issue is most acute for petroleum-derived fuels, where there is a significant mismatch between producer and consumer countries.

Both of these concerns — environment and energy security — motivate assessing the potential for alternative feedstocks for jet fuel production, and technologies for converting alternative feedstocks to jet fuel. AeroAstro's Laboratory for Aviation and the Environment (LAE) is researching a broad set of possible feedstocks and feedstock-to- fuel conversion technologies with the goal of quantifying their net environmental impacts and costs. The purpose of this research is to provide independent and impartial information to policy-makers, the aviation and fuel industries, and NGOs on the environmental and economic impacts of alternative jet fuels.

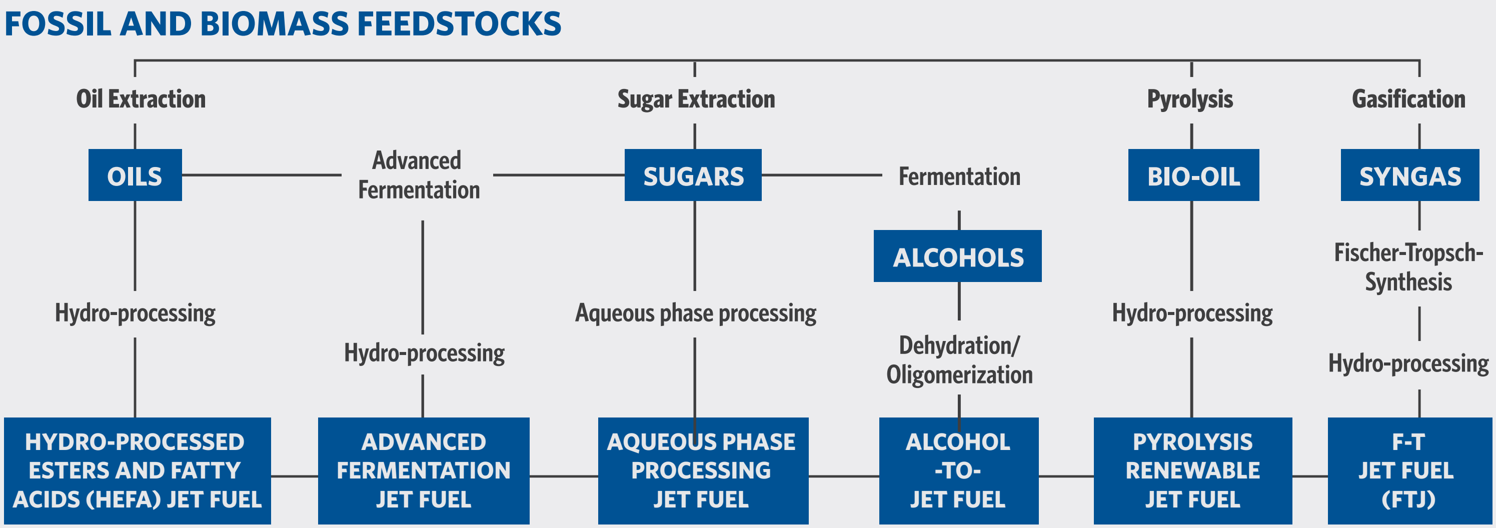
While the AeroAstro Laboratory for Aviation and the Environment's alternative fuels work has a focus on drop-in fuels compatible with existing aircraft designs and fueling infrastructure, it's also assessing other fuels that would require design/infrastructure modifications. (Shutterstock)

The current civil fleet and associated refueling infrastructure is worth trillions of dollars, and the aircraft that comprise the fleet have a lifespan of some 30 years once in service. Given the length of aircraft design, production, and service lifecycles, it is likely that some current aircraft designs will be in service well beyond the mid-21st century. Furthermore, Jet A and other kerosene-type jet fuels have proven reliable over a long period, and a global transport and handling infrastructure exists for these fuels. This means that the fuels that have greatest potential to significantly impact the environmental performance of aircraft for the coming decades are likely to be "drop-in" jet fuels; that is, those that function in existing aircraft and fueling infrastructure and typically meet the current Jet A specification. LAE's alternative fuels work has a focus on drop-in fuels, but we are also assessing other fuels that would require more major aircraft design and refueling infrastructure changes, particularly cryogenic fuels such as liquefied natural gas.

FROM FEEDSTOCK TO FUEL

In addition to petroleum the current "baseline" fuel against which we compare alternatives, jet fuel feedstocks can be other fossil sources or biomass. These are then converted to drop-in jet fuels through different possible processes.

The Fischer-Tropsch process for converting a "syngas" (carbon monoxide and hydrogen) to a fuel has been around for the better part of a century. It is still very much relevant today and can be used to convert various types of gasified biomass such as switchgrass and willow, or fossil fuels like coal and natural gas, to drop-in jet fuel.



AeroAstro's Laboratory for Aviation and the Environment is assessing these feedstock-to-fuel pathways for their environmental and economic impact. Each begins with a biomass or fossil feedstock, which is then converted to a "drop-in" (direct replacement) jet fuel.

The hydroprocessed esters and fatty acids (HEFA) process converts oils like palm, rapeseed, or soy, or waste animal fats into HEFA jet fuel. For example, hydroprocessing 100 tons of soybean oil can result in 49 tons of jet fuel as well as other products such as diesel and naptha.

Energy-rich sugars can be extracted from sugary (e.g., sugarcane), starchy (e.g., corn grain), or lignocellulocic (e.g., switchgrass) feedstocks. These can then be converted to alcohols via conventional fermentation, which then needs significant additional processing to create jet fuel. Alternatively, advanced fermentation using engineered microorganisms can directly yield a hydrocarbon that is relatively similar to jet fuel. Thermochemical methods to extract sugars in aqueous phase are also being developed.

Finally, oils suitable for hydroprocessing into a component of jet fuel can be created by pyrolysis (oxygen-free "burning") of feedstocks such as forest residues. Pyrolysis tends to result in aromatic hydrocarbons, which are a necessary component of jet fuels today. As such, for a fully synthetic jet fuel, pyrolysis could be used to create the aromatic component with other processes being used for the bulk of the fuel.

The lifecycle of alternative jet fuel with associated greenhouse and other emissions.

WELL-TO-WAKE, FIELD-TO-FLIGHT

When an alternative jet fuel is burned it results in direct emissions of CO_2 that are almost identical to conventional jet fuel. This is to be expected; because the fuel is "drop-in" it is chemically similar to conventional fuel. However, biomass-derived alternative jet fuels have the potential to reduce *lifecycle* CO_2 emissions. This is because the carbon in the fuel came from the atmosphere originally (via photosynthesis), thus this component of the carbon is "closed-loop." While this does offer the potential for a carbon-neutral fuel in theory, in practice the situation is more complex. In particular, converting biomass into jet fuel requires energy and materials often resulting in CO_2 emissions. For example, hydroprocessing requires hydrogen, which is created from natural gas (mainly methane, CH_4). Conversion of methane to hydrogen entails the C in the CH_4 being vented to the atmosphere as CO_2, with the result being H_2. Also, processes that require electricity or heat can result in CO_2 emissions, as does the transportation of the biomass feedstock and resulting jet fuel.

To assess the environmental and economic performance of each feedstock-to-fuel pathway, the material and energy flows associated with each step of the fuel's lifecycle is tracked. This is known as "lifecycle assessment," where the aim is to determine the net CO_2 emissions associated with the lifecycle of a fuel including initial land use change for cultivation, biomass cultivation, biomass transport, conversion to a jet fuel, credits or debits for co-products of this process, fuel transport, and fuel production. Additionally, indirect changes in land use induced by increased biomass cultivation for fuel can be estimated. This competition for land gives rise to concerns over potential impacts on food supply and prices.

Lifecycle assessments typically consider CO_2-equivalent greenhouse gas (GHG) emissions. Our results show that use of alternative fossil feedstocks always result in greater GHG emissions than conventional jet fuel. For example, coal- derived F-T jet fuel has more than double the carbon intensity of conventional jet fuel, while natural gas as a feedstock still results in a quarter more CO_2 emissions than Jet A. On the other hand, many biomass-derived jet fuels have lower lifecycle GHG emissions than conventional fuels. For example, switchgrass to F-T jet has a carbon intensity about 80% lower than regular Jet A.

Professor Steven Barrett directs the Laboratory for Aviation and the Environment's research into a broad set of possible feedstocks and feedstock-to-fuel conversion technologies with the goal of quantifying their net aviation environmental impacts and costs. (William Litant)

More recent LAE lifecycle assessment work has focused on feedstock-to-fuel pathways including waste oils and fats to HEFA jet fuel, advanced fermentation of sugary, starchy and lignocellulocic feedstocks, and thermochemical (aqueous phase) processing of feedstocks. These new assessments indicate significant potential for reduced lifecycle GHG emissions.

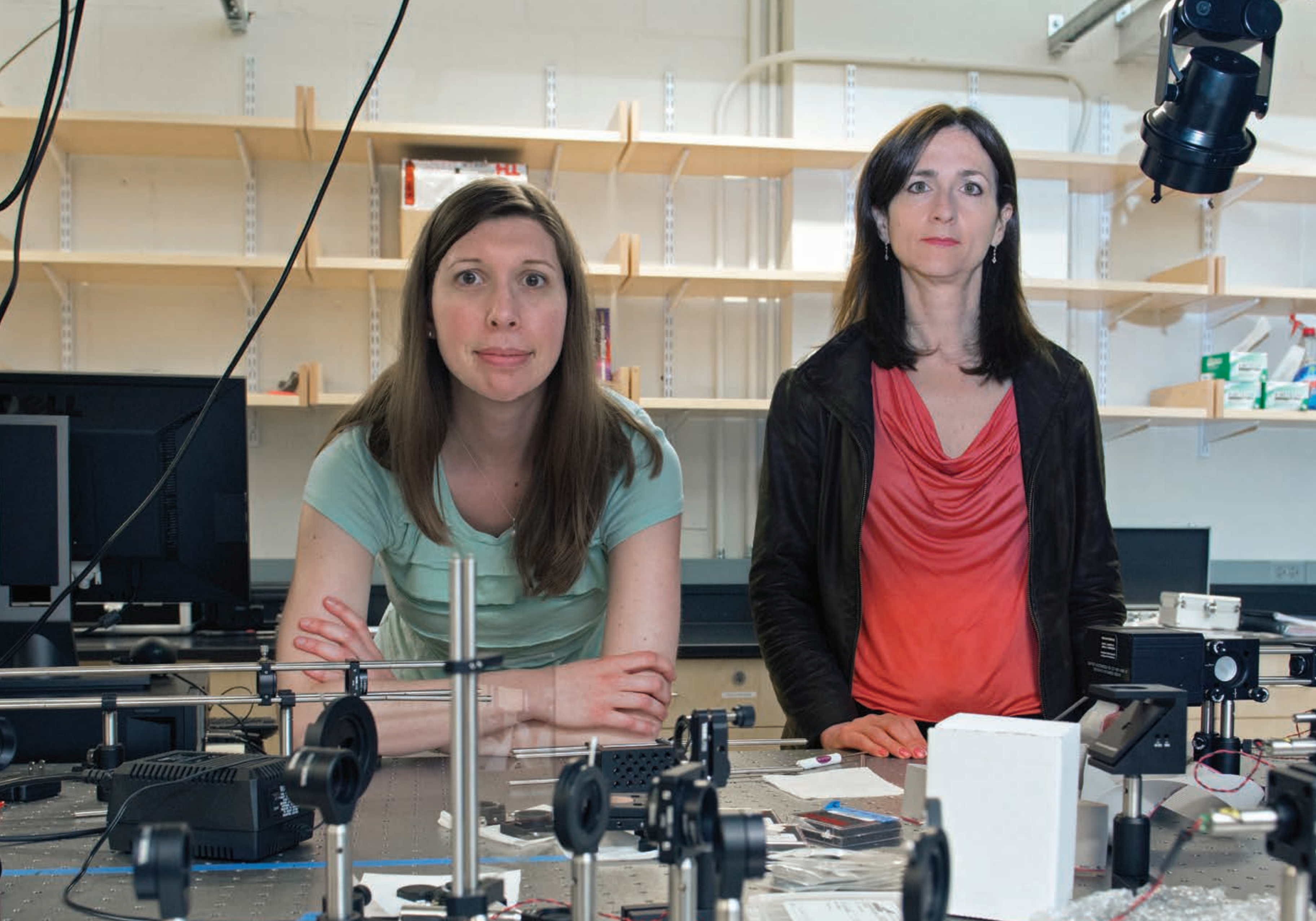
BEYOND CO_2

Lifecycle assessments typically focus on "biogeochemical" effects; that is, net fluxes of greenhouse gases to and from the atmosphere. We are now moving towards including "biogeophysical" effects in lifecycle assessments. These are the changes in the radiation balance of the planet due to physical changes. For example, large-scale biomass cultivation for fuel production results in changes to the average planetary albedo. Our research indicates that this effect is usually cooling, and of a similar order to the biogeochemical effects. A second example relates to contrails — the line-shaped clouds that aircraft sometimes leave in their wake. These are thought to significantly contribute to the climate warming attributable to aviation. Our latest research indicates that combustion of alternative fuels may result in contrails that are optically thinner, so may result in less warming than contrails produced by combustion of conventional jet fuel. We are also assessing the air quality and human health implications of alternative jet fuels, which typically burn cleaner than their conventional counterparts. Beyond the potentially significant benefits of many alternative jet fuel options, there are also a range of downsides, some of which we are investigating. In particular, fresh water use in biomass cultivation and fuel production is a potential concern. Our calculations indicate that use of unirrigated biomass for alternative fuel production results in a water intensity about the same as conventional jet fuel. However, maximizing biomass yield would result in many times more fresh water consumption than regular Jet A — in some cases hundreds of liters of water per liter of fuel. A second potential disadvantage is the "environmental opportunity cost" of using biomass for alternative jet fuel production; that is, the extent to which more GHG emissions could have been offset if the biomass were used for a different purpose. For example, rather than expending energy on converting biomass to a tightly specified high quality fuel like Jet A, it could be directly burned in a combined heat and power plant, potentially offsetting CO_2-intensive coal-fired generation. Finally, we are assessing the production costs of different feedstock-to-fuel pathways. This is critical for both economic and environmental reasons — a fuel that is too expensive will not be adopted and, thus, will result in no environmental benefit.

A non-competitive fuel will not penetrate the market and the lowest cost environmental mitigation measures will enable the greatest reduction in emissions.

Laboratory for Aviation and the Environment research indicates that combustion of alternative fuels may result in contrails that are optically thinner, so may result in less warming than contrails produced by combustion of conventional jet fuel. (US Air Force)

STEVEN BARRETT is an AeroAstro Assistant Professor of Aeronautics and Astronautics and director of the Laboratory for Aviation and the Environment (http://lae.mit.edu). The goal of his research is to advance understanding of the air quality and climate impacts of aviation and other transportation emissions, and to develop technological, fuel-based, and regulatory strategies to mitigate these impacts. Steven Barrett can be reached at sbarrett@mit.edu.



AeroAstro Professor Kerri Cahoy (left) is joined by Professor Sara Seager of the Department of Earth, Atmospheric, and Planetary Sciences in Cahoy's Wavefront Control Laboratory. They're standing behind an optical table simulation of a space telescope that will use a coronagraph to take direct images of Earth-like exoplanets around other stars. (William Litant)

A SYMBIOTIC PARTNERSHIP

When EAPS explores the cosmos, AeroAstro gets it there

By Dick Dahl

For most of their existences, MIT's Department of Aeronautics and Astronautics and the Department of Earth, Atmospheric and Planetary Sciences operated independently of one another.

But the last few years have seen a significant change, with an increasing emphasis on bringing together the engineering students and faculty of AeroAstro, a department in the School of Engineering, with their EAPS counterparts in the School of Science.

AeroAstro and EAPS have worked together on a variety of missions and projects, some courses are now cross listed between the two departments, some faculty members are teaching in both, and the prospects for ever greater collaboration between Aero Astro and EAPS appear strong.

The reason for this convergence is obvious. Even though the two departments are inherently different — one produces engineers and the other scientists — the students and faculty in each share an obvious common interest in the sky and the heavens. Meanwhile, real-world technological and economic forces are encouraging engineering/science collaborations in aeronautics and astronautics like never before.

A 'SYMBIOTIC RELATIONSHIP'

"One way to understand how we work with EAPS is that EAPS is interested in the science — they're interested in launching satellites to acquire the data to support the science, to measure properties of the atmosphere — and we actually make the platform," says Professor Jaime Peraire, AeroAstro department head.

But he points out that the real push for greater collaboration between the two disciplines is being driven by technological change and economics. For example, he says, satellites have become much smaller — the one-cubic-liter CubeSats now used for space research have greatly reduced the cost of launching and operating satellites.

“This means that launching satellites is a lot more doable than it used to be, and it means we can do interesting things within the university,” Peraire says.

MIT faculty who have worked on these AeroAstro/EAPS collaborations say bringing the science and the engineering together is essential for the creation of effective missions and projects because, in fact, they need each other.

“I’d call it a symbiotic relationship because, essentially, in Aero Astro they build stuff and in planetary science we need to look for stuff,” says Sara Seager, an EAPS professor of planetary science and physics who also has taught in the AeroAstro Department. “So it’s kind of a natural fit and it’s really beneficial because we want to train students who can work at boundary — scientists who can do engineering and engineers who can do planetary science.”

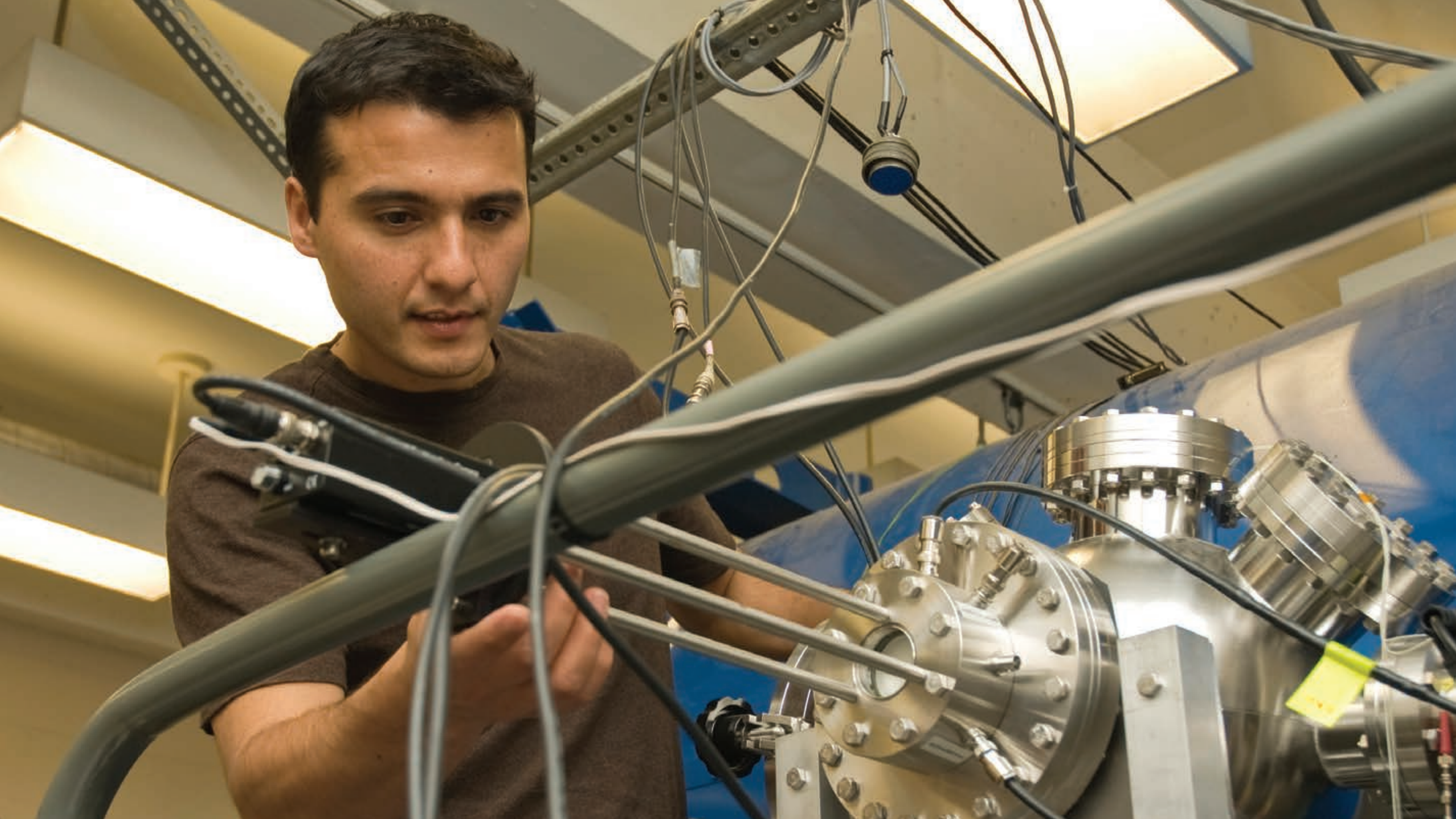
“It’s kind of a natural fit and it’s really beneficial because we want to train students who can work at boundary — scientists who can do engineering and engineers who can do planetary science.”

- EAPS PROFESSOR SARA SEAGER

“Historically, engineering and science have been kind of divorced,” says Paulo Lozano, AeroAstro associate professor and director of the Space Propulsion Lab. “But it’s very important for scientists to talk to engineers and understand better the constraints of engineering when designing their missions. Many times engineers get the requirements from scientists, and many times they are well beyond the capabilities of existing engineering. It’s helpful to have bidirectional conversations because many times the engineers can say, ‘We cannot really do this right now.’”

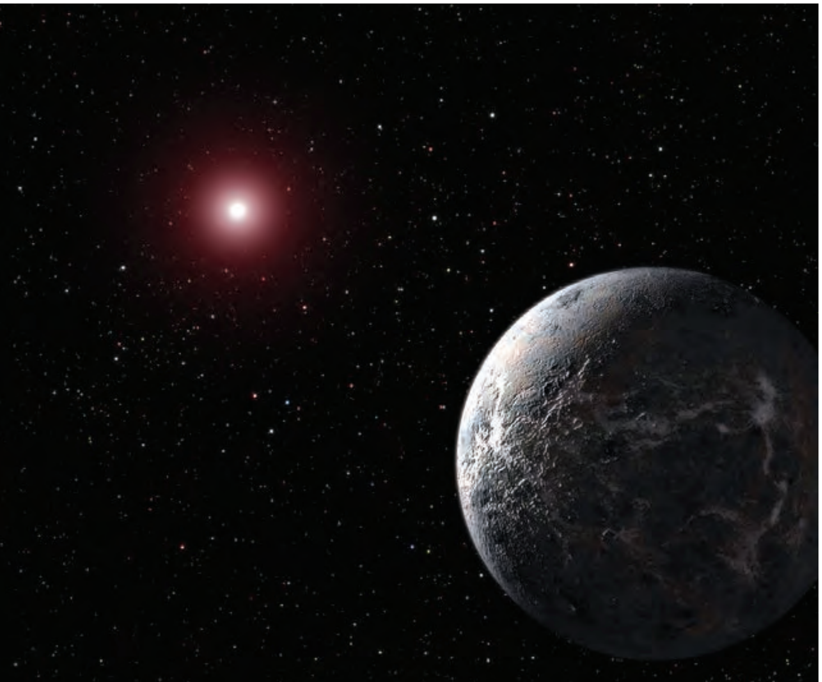
In similar fashion, engineers need to understand what the scientists need from them.

“There’s often a lack of understanding between the two of how changing one thing might affect the other and what the limitations are of a system and what’s feasible and what’s infeasible,”



AeroAstro Space Propulsion Lab head Professor Paulo Lozano notes that a benefit of AeroAstro/EAPS partnerships is engineers and scientists sharing needs and abilities. "Many times engineers get the requirements from scientists, and many times they are well beyond the capabilities of existing engineering," he says. (William Litant)

says Kerri Cahoy, who came to MIT in 2011 as the first faculty member with a joint appointment in the two departments. "The job of the scientist is to communicate to them that 'if you can't point over here for this long, or if you wiggle a little bit, the measurements are going to be really messed up,' or 'if you don't have enough power for me, I'm not going to able to make a measurement.'"



Extrasolar planets, or exoplanets, are planets outside our Solar System like this one orbiting the star Kepler 22, shown in an artist's concept. ExoplanetSat, a cooperative EAPS/AeroAstro venture, will monitor individual, bright, nearby stars for the purpose of finding exoplanets. (NASA)

AeroAstro professor and Space Systems Laboratory director David Miller characterizes the interactions as creative tension involving "science-driven technology and technology-enabled science."

"Some call it 'technology pull' and 'technology push,'" he says. "Technology pull is where there's some science goal and they need something to be done so they're pulling the technology to allow that to happen. Technology push is where there's some invention and it's essentially a solution looking for a problem, so to speak. By working with the scientists we might find the actual best match for that new technological invention."

EXPLORING SPACE, WATCHING OUT FOR EARTH

Of numerous current and planned collaborative projects, one example involves Seager's exoplanet (planets outside our solar system) research and the planned deployment of a small satellite, ExoplanetSat, which will monitor individual, bright, nearby stars for the purpose of finding orbiting exoplanets. ExoplanetSat will provide the kind of precise, targeted search that is necessary for identifying planets and their properties — an impossible task for even the most sophisticated of telescopes.

A single ExoplanetSat focusing on one star would have the capability to detect the minute dimming that would occur if a planet crosses in front of it during its orbit. Miller has an AeroAstro team that's building the flight system, which they've already prototyped. The first launch is confirmed through NASA's ELaNa (Educational Launch of Nanosatellites) Program, although, as of this writing, a launch date is not confirmed. According to Seager, plans call for the eventual launch of a fleet of nanosatellites to monitor individual stars.

MIT student involvement in that project began in 2010 when Seager and Miller collaborated to offer a three-semester-long course that used the development of ExoplanetSat as its teaching method, offering it jointly to seniors in AeroAstro and EAPS in the Space Systems Engineering capstone class. The ExoplanetSat project is now more "mature" in its development, Seager says, so it is no longer offered to undergraduates however, a number of graduate students are still involved.

Another collaborative project calls for building an X-ray imaging spectrometer to be deployed as part of the OSIRIS-REx NASA mission to asteroid 1999 RQ36, which may pose a threat to Earth.

Lozano is involved in that project, focusing on developing propulsion systems for small satellites. He says the involvement of scientists in his endeavor has been valuable.

"It's been very useful for us in designing the requirements of our propulsion system because we know exactly what they need," he says. "For example, in this particular application of looking for exosolar planets, we know exactly how much precision they need. That allows us to tailor the properties of our propulsion system to satisfy those requirements."

Another collaborative project calls for building an X-ray imaging spectrometer to be deployed as part of the OSIRIS-REx NASA mission to asteroid 1999 RQ36, which may pose a threat to Earth when it passes close by in 2165. Dr. Rebecca Masterson runs the program, Miller is the PI, and EAPS Professor Richard Binzel is extremely involved in the project where students are building the spectrometer, the purpose of which is to provide X-ray spectra from different areas of the asteroid's surface to determine elemental composition.

The launch is set for 2016, with a return date in 2023.

ASSESSING EMISSION IMPACT

AeroAstro Professor Steven Barrett, who heads the Laboratory for Aviation and Environment, is collaborating with EAPS and the MIT Joint Program on the Science and Policy of Global Change to better assess long-term aircraft emission environmental impacts.

Barrett has been working with EAPS' TEPCO Professor of Atmospheric science Ronald G. Prinn on the project, using the modeling capabilities that EAPS has developed over the last 20 years for a range of policy analyses used to inform the Intergovernmental Panel on Climate Change.

The professors say that the educational benefit for students taking part in engineering/science collaborations is invaluable.

However, Barrett says, it's never been used for aviation. So what he's doing is using EAPS' "sophisticated tools" and applying them to aviation for the purpose of "understanding what would be the impacts of aviation on global temperatures and climate out to the end of the 21st century."

His findings could have an impact on broad public policy.

"The FAA has asked us to take this first cut at the work and make that into a kind of applied policy analysis," Barrett says. "So it could potentially be used to inform the U.S. government and its environmental policy decisions on aviation."

UNIQUE EDUCATION OPPORTUNITY, STRENGTHENS DEPARTMENTS

The professors say that the educational benefit for students taking part in engineering/science collaborations is invaluable.

"I've been surprised by the shared interest and joy that the engineering students had in being connected to planetary science, even from the students who didn't really know that they would like it," says Seager. "There's a purpose in engineering, of course, but there's a separate motivation that showed impact beyond their own engineering course."

Cahoy says that for engineering students, “one of the nice parts about having the collaboration with EAPS and having students in classes going both ways is that they get to say, ‘Oh, here’s the cool application that the system is actually achieving.’”

The crossover between AeroAstro and EAPS will only become stronger, these professors believe. In fact, professors say, the idea of creating an MIT “Small Satellite Center” to be operated by the two departments arose at a recent joint AeroAstro/EAPS faculty meeting.

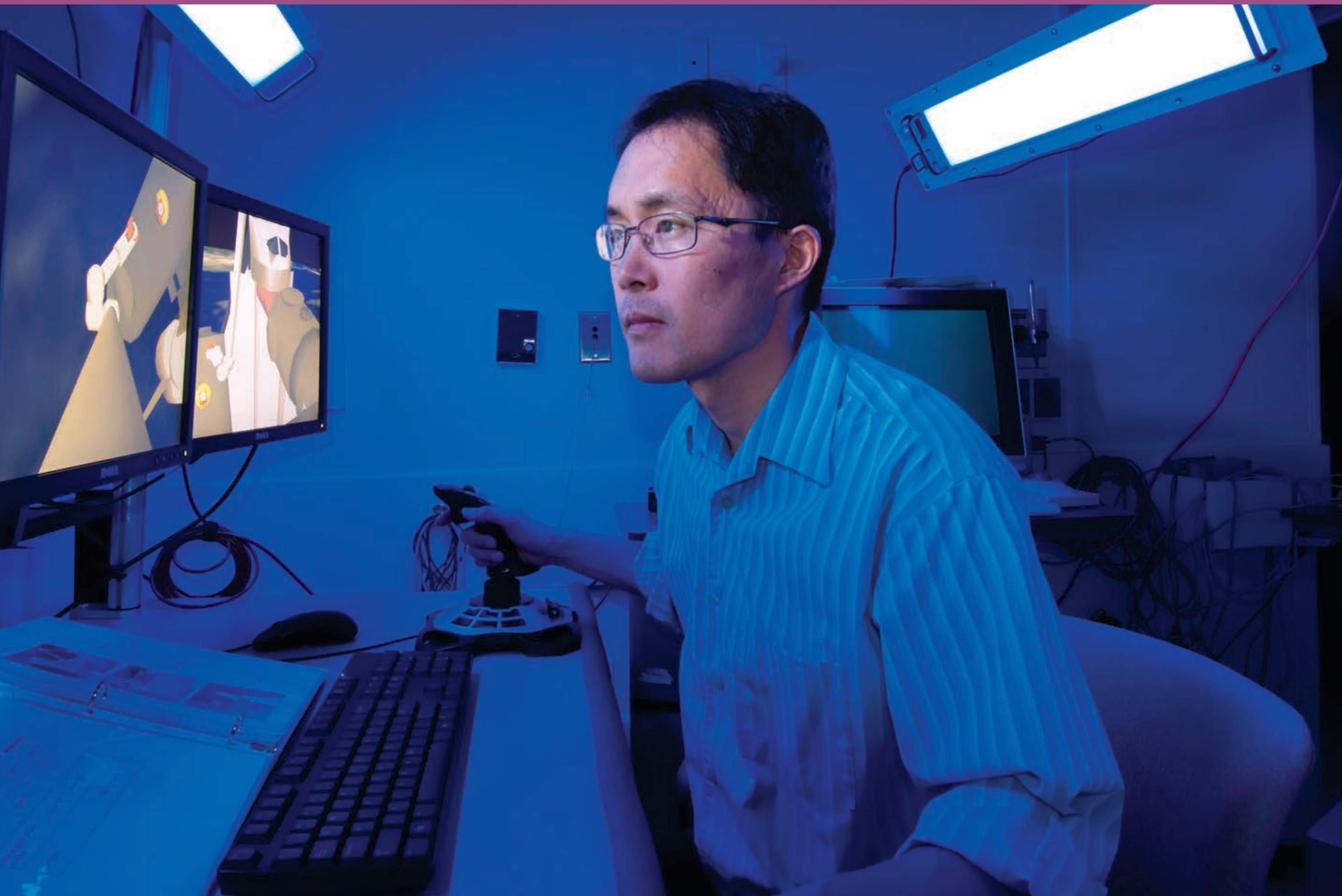
“From our perspective, we’re now beginning to train a new kind of aerospace engineer,” Lozano says. “Our aerospace engineers now know what the mission is about, what the science is about, and they design according to these requirements within the context of the mission.”

The professors also believe that the collaborations create stronger departments for both AeroAstro and EAPS.

“I think it strengthens complementary capabilities because they’re bringing skills to the table that we do not have and vice versa,” says Peraire. “It’s definitely a win-win.”

DICK DAHL is a freelance writer who lives in West Roxbury, Mass. He may be reached at rcdahl@gmail.com.

Man Vehicle Lab research scientist Andrew Liu simulates a grappling operation with the same type of hand controllers used to operate the International Space Station's robotic arm. This MVL project examines effects of fatigue resulting from sleep debt, hours awake, and changes in sleep/wake time on performance of a complex task like telerobotics (remote operation of robots) and whether countermeasures such as blue-enriched white light are effective in reducing fatigue. (Andrew Liu)



A HALF-CENTURY OF RESEARCH IN AVIATION, SPACE, AND CLINICAL APPLICATIONS

The Man Vehicle Lab at 50

By Larry Young

Like so many other out of the box innovations in the AeroAstro Department, the ideas that led to the Man Vehicle Lab came from Charles Stark "Doc" Draper.

It was around 1960. Doc had a long-standing interest in the proper roles of man and machine in guidance and control.

Doc, who headed both the MIT Instrumentation Lab and AeroAstro, hired me as an assistant professor in 1962 to introduce the department to what we now call biomedical engineering. He lined me up with Professor Y.T. Li, an amazingly innovative inventor. Together, Li and I jumped on the NASA manned spaceflight bandwagon and began to study humans as biological inertial guidance systems.

We built our first linear acceleration sled in Building 17A (the old blow-down wind tunnel) and thus was born the Man Vehicle Lab, 50 years ago. Our goal since that time has been to better define the physiological and cognitive limitations of the pilots and passengers in airplanes and in spacecraft. We aim to optimize human-vehicle system effectiveness and safety.

To mark the half-century of research in aviation, space, and clinical applications, we and more than 100 alumni and guests celebrated "mvl@50" on September 14, 2012. (Visit http://mvl.mit.edu/MVL-50th.htm to take a look at the celebration videos and pictures of 50 years of the MVL and its alums, including a research memoir, a listing of theses, and of about 900 publications.) Although the "Man" in Man Vehicle is no longer exclusive — many of our students and subjects are women — MVL recognition and reputation are so strong that we retain the name and the perhaps even better known initials.

We've had only three directors over the lab's half century. Initial director Y.T. Li contributed his wisdom, ingenuity, and some of his personal capital, to the earliest decade. He concentrated on mechanically emulating the human balance system for the dynamic stability of narrow-wheel-base vehicles, suitable for the crowded streets of Asia.

Dr. Li passed the directorship to me in 1970, and I handed it to current director Charles Oman in 1992. Chuck developed closer external links to Draper Laboratory, the U.S. Department of Transportation's Volpe Center, and to the vestibular research team at the Massachusetts Eye and Ear Infirmary. Y.T., Chuck, and I were last together at a 2009 MIT Symposium in honor of Chuck's 65th birthday. Dr. Li passed away in 2011 at age 97.

BIOMECHANICS, SPORTS, EXTREME ENVIRONMENTS

It's not surprising that the faculty and many of the students maintain interests in biomechanics in sports and extreme environments. Three of us were varsity alpine skiers in college and four of us are experienced sailors. Oman writes and lectures to ocean sailboat racers on avoiding seasickness. Professor Dava Newman set the women's speed record for a human powered hydrofoil, and spent a sabbatical sailing around the world. Former AeroAstro Professor Steve Bussolari, who's now on the Director's Office Staff at Lincoln Lab, designed the pilot interface for Daedalus, MIT's record-setting man-powered airplane. Former astronaut Jeff Hoffman's space missions included spacewalks to repair the Hubble Space Telescope and to fix a satellite. And, my research on alpine ski bindings contributed to standards that brought the accident rate on the slopes down by a factor of five. We continue to work on head-to toe protective gear — for athletes as well as astronauts.

Astronaut disorientation, space sickness, and deconditioning remain challenges to space exploration and space tourism.

Most of the 200 or so graduate students in the MVL over the past 50 years have applied physiology or psychology to aviation or space. Astronaut disorientation, space sickness, and deconditioning remain challenges to space exploration and space tourism. Disorientation in airplanes and in motion based fight simulators is similarly challenging. Clinical applications to patients suffering from vertigo and balance disorders provided another avenue for our research. We modeled the physics and neurophysiology of the vestibular system in the inner ear and its connections to muscles. We contributed to understanding posture and balance, as well as the astronaut challenge of walking under the reduced gravity of the Moon and Mars.

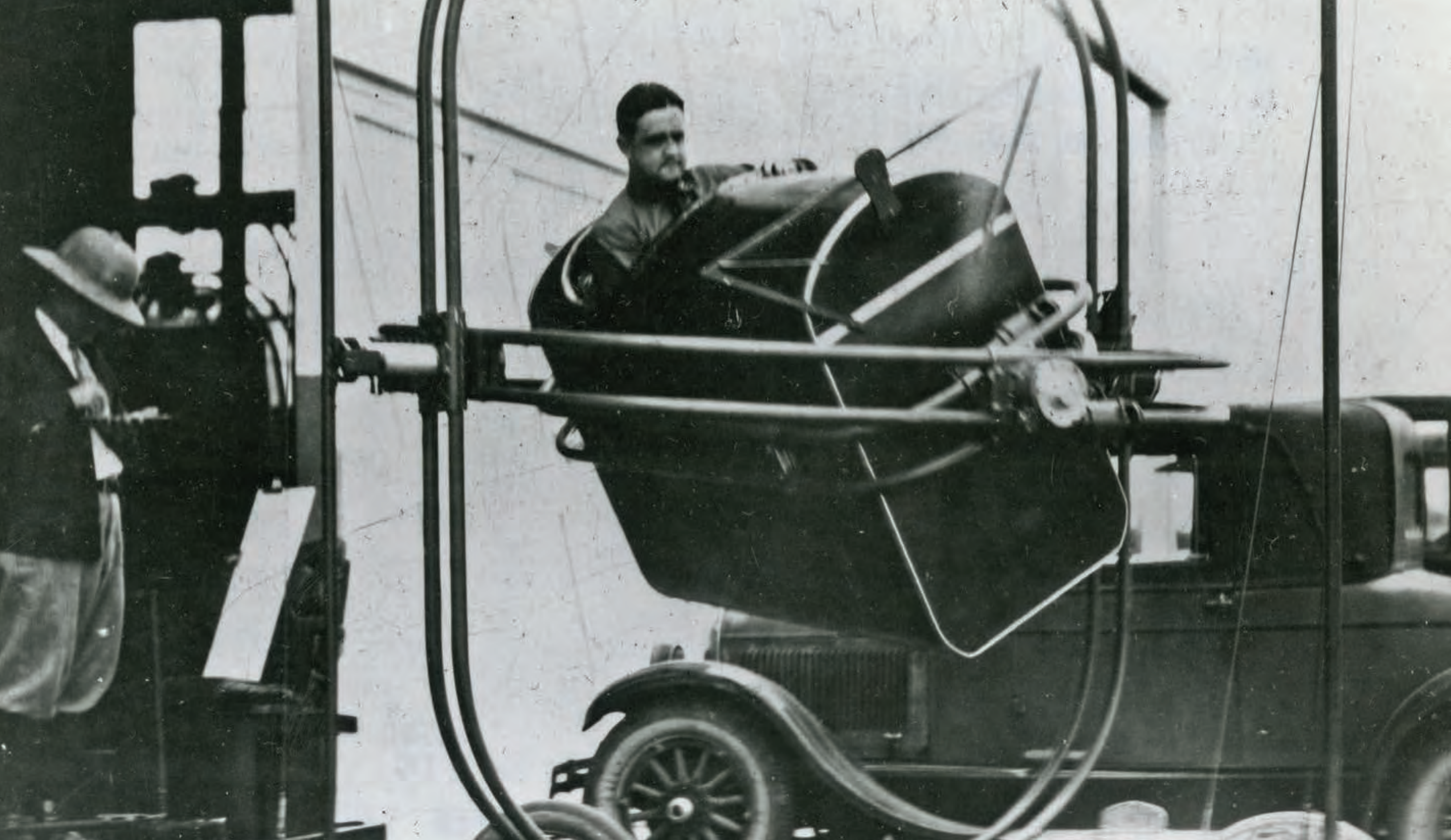
Pictured at a 2009 symposium, the last time they were together, are the three men whose directorships span the 50-year history of the MVL: (from left) current director Charles Oman (1992–), initial director Y.T. Li (1962–1970), and Larry Young (1970–1992). Li passed away in 2011 at age 97.

FLIGHT SIMULATOR REALISM

Whether flight simulators are used for pilot training or for flight research, we want the sensation of motion in a simulator to feel close to that of the real airplane. With that goal in mind, we developed simulator motion-drive algorithms based upon mathematical models of the sensors in the inner ear, and concepts of how the brain blends information from the various senses.

At this time, we are dealing with the disorientation that occurs when a pilot pitches or rolls a vehicle in a gravity field other than that of the Earth — say in lunar (1/6 g) or Martian (3/8 g) gravity — and how it affects the ability to control a descent. We use a large human centrifuge at NASTAR in Pennsylvania to study the related disorientation problem occurring when a pilot, who is in a high-g turn, makes a head movement and feels that the plane has rolled further than it actually has (the "excess-g illusion").

Since human space flight's earliest days, MVL's been involved. For instance, we looked into allowing Apollo astronauts the option of taking over control of the first stage of the Saturn rocket — and decided it was too likely to excite the dangerous bending modes of the rocket. Professors Sandy Alexander, Steve Busollari, and then Dava Newman studied effects of astronaut movement on spacecraft motion, making measurements on the MIR Russian space station. With the introduction of the Space Shuttle and Spacelab, its pressurized laboratory, the MVL became



Doc Draper puts a trainer through its paces at Brooks Field in Texas in 1926. It was Doc's passion for flying and automated guidance and control that led to the creation of the Man Vehicle Lab. (MIT Museum)

a den of "space cadets." We flew major experiments dealing with human balance and orientation on a dozen flights, from the first Spacelab to the last, and learned how gravitational forces are measured and interpreted by the body. We studied how the nervous system reorganizes to adapt to life in weightlessness, as well as how it recovers after return to Earth. Newman, Oman, and I were literally up to our ears in space flight, and our students had the chance to test and train astronauts as well as to try our MIT-built equipment during parabolic flights. It was a blast!

MVL ASTRONAUTS, NASA TIES

Not surprisingly, a number of us wanted to be astronauts, and several succeeded. Byron Lichtenberg became America's first payload specialist, a non-career astronaut brought in for special knowledge of specific payloads. In Byron's case, it was biomedical engineering, and he flew in space twice, helping to establish the desirability of flying technical specialists. Steve Robinson, one of our post-docs who worked on the Spacelab post-flight tests, became a mission specialist who flew four Shuttle missions. Mike Massamino (most recently of "Big Bang Theory" television program notoriety) and Nick Patrick also studied with us, and similarly had successful careers in space. Even I spent two years in training as a payload specialist for a Spacelab mission. As the alternate (or "half-astronaut" as my family irreverently called me), I served as payload communicator rather than going into orbit. Our most experienced astronaut and current faculty colleague is Jeff Hoffman, who returned to MIT following his five Space Shuttle missions and a NASA diplomatic post in Paris. Jeff combines his extensive space flight experience with his science interests to work on space architecture and the planning of exploration missions. TALARIS, his "lunar hopping" concept device to sample numerous sites on the lunar surface, was prototyped by his students and has attracted major interest.

Our most experienced astronaut and current faculty colleague is Jeff Hoffman, who returned to MIT following his five Space Shuttle missions and a NASA diplomatic post in Paris.

Dava Newman's long-standing (or more properly, long-walking) research in the biomechanics of extravehicular activity locomotion entailed underwater walking, partial suspension treadmills, and the development of Biosuits — radically different space suits, visually evoking a diver's wetsuit, which do not depend on gas to maintain pressure on the skin.

Our close ties to the space agency extended to frequent faculty and student NASA research tours. At NASA Langley, Chuck Oman, Johannes Dichgans, and I used their large Dual Maneuvering Spheres to quantify visually induced motion (the kind of movement illusion you get when the train on the neighboring track slowly moves away). At NASA Ames we used most of their large motion simulators, including the big outdoor elevator, to test our theories of human motion

For Spacelab's 1983 maiden voyage the MVL prepared experiments to measure changes in astronaut balance. Crew member and MIT/MVL alumnus Byron Lichenberg (SM '75, ScD '79) is shown here during pre-flight acceleration on the lab's "vestibular sled." Instruments inside the box-like helmet measure his eye movements and movement perception. (MVL)

perception, most recently in lunar landing. Dan Merfeld also tested monkey eye movements in their vestibular test lab and Dava Newman built an underwater treadmill to investigate partial gravity locomotion. Extensive astronaut pre-post flight-testing required us to establish labs at the Kennedy Space Center in Florida, at Dryden Flight Research Facility in the high desert of California, and in Houston at the Johnson Space Center. Each time, the MIT students proved their worth to the NASA "pros" and built up a wealth of space experiences to tell their children about.

Like many MIT labs, MVL sprouted successful spinoffs. Lew Nashner turned the posture control platform of his thesis into Neurocom, the world's leading manufacturer of balance platforms and now a division of Natus. Greg Zacharias founded Charles River Analytics to apply pilot modeling to real control problems in aviation. Byron Lichtenberg and Anthony Arrott used their Spacelab experience to found Payload Systems, which is now part of Aurora Flight Sciences. Peter Diamandis, of X-Prize fame, also founded Zero-G, along with Byron, to commercialize parabolic flight.

FACULTY AND VISITING SCHOLARS

Over the years, MVL has been privileged to have a series of dedicated faculty and visiting scholars. Jacob Meiry brought us through the transition from analog to digital and Ren Curry and then Steve Bussolari introduced modern control theory to our simulator motion algorithms. Bob Kenyon showed how modern biomedical instrumentation could be used for our space experiments. Visiting Israeli professors Rafi Sivan and Josh Zeevi left their mark on research and teaching, as did many distinguished international researchers. Outstanding postdocs, too many to mention here, kept the lab running and offered the guidance needed by our students — particularly during the hectic years of our space missions. Our staff members, especially Sherry Modestino and Bob Renshaw, provided the personal and technical glue that kept the whole lab together and created a sense of purpose and community that is still said to be the envy of all.

MVL is turning toward long duration space flight, including artificial gravity (centrifugation) and g-loading suits, to counter-act microgravity deconditioning.

To this day, we enjoy the humor and statistical guidance of Alan Natapoff, the human factors expertise of Andy Liu, and the extraordinary administrative talents of Liz Zotos.

As we enter our second half-century, the MVL is turning toward long duration space flight, including artificial gravity (centrifugation) and g-loading suits, to counteract microgravity deconditioning. Virtual reality and artificial intelligence play increasing roles as the interaction of people and machines evolve — and we continue striving to answer Doc Draper's challenge: to use both pilots and computers appropriately, in the air, in space, and now in the clinic.

LARRY YOUNG is the Apollo Program Professor of Astronautics. He is a former director of the Man Vehicle Lab and of the National Space Biomedical Research Institute. He can be reached at lry@mit.edu.

FACULTY INTERVIEW:

A visit with Dr. Sheila Widnall

By William T.G. Litant

Dr. Sheila Evans Widnall (AeroAstro S.B. '60, S.M. '61, Sc.D. '64) joined the Department of Aeronautics and Astronautics faculty in 1964, MIT's first woman professor of engineering.

Sheila Widnall was MIT faculty chair from 1979 to 1981. In 1988, she was president of the American Association for the Advancement of Science. Widnall was serving as MIT associate provost when, in 1993, President Bill Clinton nominated her as Secretary of the Air Force, a position in which she served from 1992 to 1993. To this day, she is the only woman to have headed a branch of the United States military. As Secretary of the Air Force, Dr. Widnall was responsible for all the affairs of the Department of the Air Force including recruiting, organizing, training, administration, logistical support, maintenance, and welfare of personnel. During this time, the Air Force issued its long range vision statement: "Global Engagement: A Vision for the 21st Century Air Force," which defined the path from the Air and Space force of today to the Space and Air Force of the next century. She also co-chaired the Department of Defense Task Force on Sexual Harassment and Discrimination

Widnall was elected to the National Academy of Engineering in 1995, eventually receiving that organization's Arthur M. Bueche Award. In 1998, the year following her return to MIT, she was presented the title of Institute Professor, MIT's highest faculty honor. In 2003, NASA appointed her to the Columbia Accident Investigation board, convened to investigate the shuttle's February 1, 2003 destruction during re-entry. In 2010, she was named to an independent panel that would advise Toyota as it sought to address quality and safety issues.

Widnall's research interests are many: from boundary layer stability, unsteady hydrodynamic loads on fully wetted and supercavitating hydrofoils of finite span and unsteady lifting-surface theory; to aircraft-wake studies, turbulence and transition. She's currently teaching AeroAstro class 16.07 Intro to Aerodynamics.

Recently, AeroAstro sat down with Dr. Widnall to discuss her fascinating career.

AeroAstro: Tell us about when you realized you were interested in aviation.

Widnall: I was born on the final approach to McChord Air Force Base in Washington State. As I was growing up, planes were constantly landing, mostly fighters but some transports. The other thing was that if you live in Tacoma, and you're going to be an engineer, you figure you're going to work for Boeing.

AeroAstro: Was it unusual for a young girl in the '40s and '50s to be interested in airplanes?

Widnall: I suppose, but I was raised to be very independent. My father rode bulls in the rodeo, and my mother was a juvenile probation officer, so she worked, which was very unusual in those days. His family lost their ranch in the Depression, and he was sent into the world with one horse and one saddle. So he had to make his own way. Mom was a social worker so she went around to people and provided government support, aid, and comfort. She had a fulltime job.

AeroAstro: Were there others in your family?

Widnall: I have a younger sister. She started out to be a cop, a policewoman. Her husband was teaching junior high. He was going to school and she was going out armed. One day she said to herself, "What's wrong with this picture?" So she became a schoolteacher. And because of her special skills, they gave her what they called "troubled youth" at the high school level, because she was a tough gal. She dealt with kids who were right on the border between being good and being bad, and with psychological and behavioral problems. This was at the high school level. So that's a dangerous place to be.

Upon receiving her doctorate, Sheila Evans Widnall (SB '60, SM '61, ScD '64) joined the AeroAstro faculty as MIT's first woman professor of engineering. (MIT Museum)

AeroAstro: Tell us about your school years

Widnall: I went to a Catholic girl's school with nuns. That's independence breeding: it's a girls' school and your role models are very independent women. So you're not being run roughshod by guys in science class!

AeroAstro: When did science and engineering enter the picture?

Widnall: This is an interesting story. I was a junior in high school. I did a science fair project on the radioactive decay of uranium. It was a diorama of models of atoms and how they decay. That brought me to the attention of a local MIT alum who had a Ph.D. in civil engineering and had a concrete firm doing very innovative things in bridges and stadiums and all those things using pre-stressed concrete. He encouraged me to consider MIT and helped me get a scholarship from Seattle alums. There were 28 of us competing for it and they gave it to me. If I remember correctly, maybe five of us ended up at MIT from that Seattle-Tacoma area. I was the only woman.

AeroAstro: What did you think when you got to Cambridge?

Widnall: I came in 1956 with the Class of 1960. It was amazing. The two things I remember the most are that the Boston brownstones only had windows on the front and back! We didn't have brownstones in Tacoma. The other thing was, I walked in that first day, looked around, and I said to myself, "Why are there so few women here?" My MIT class had 23 women and that was more than any previous class! My freshman advisor, who was a professor of electrical engineering said, "What are *you* doing here?" I thought that was insulting. But I thrived at MIT.

AeroAstro: Did you know at that point that you would wind up in aeronautical engineering?

Widnall: I thought I'd major in physics, especially because of my science fair project on radioactive decay. But given my fascination with aerospace, by the middle of my freshman year I had chosen to go into aerospace.

AeroAstro: When did you begin to focus on becoming a member of the faculty?

Widnall: That happened almost immediately. As I graduated, I was given a post-doctoral fellowship and made a member of the faculty. So the transition was very straightforward. I had very supportive faculty, Holt Ashley and Martin Landahl.

AeroAstro: When you became MIT's first woman member of the engineering faculty, were you welcomed or did you feel resistance from some corners?

Widnall: For the most part I was welcomed. I remember some crazy things that happened. For example, it used to be that faculty would get together occasionally for dinner. Somebody remarked that now that there was a female, they might as well invite their wives. It was little things like that.

AeroAstro: What was your first area of research as a faculty member?

Widnall: I'm in fluid dynamics, in fact unsteady aerodynamics. We were developing numerical methods for calculating forces on oscillating hydrofoils and oscillating wings with non-planar configurations, like T tails and Vs and things like that. Pretty practical stuff and it was all computational.

AeroAstro: How do you think the environment's changed for young women at MIT today?

Widnall: They don't need to be as resistant, resilient, and tough-minded as I was. Today, MIT is extremely welcoming to women faculty. We have roughly 50 percent women undergraduates. I've been on the AeroAstro faculty search committees for the last few years, and last year our two hires were both women. It just happens; we've got a lot of women on our faculty, and I think it completely changed the environment for women graduate students. I think MIT has dramatically transformed. If you read old faculty meeting minutes, everybody is a "he." It's very different era.

MIT is at the leading edge, and as you pursue the leading edge, it uncovers new leading edges. It's truly a unique institution and it will continue to evolve. The strength in engineering is unmatched anywhere in the world, really. It's hard for me to say whether that's different for women than it is for men. I think most people believe that women are better at multitasking and more holistic approaches to problems. I don't know whether that's proven out in the psychiatric literature, but that's my general sense.

AeroAstro: What would you do or say to young women to encourage them? Is this a field you think people should be going into?

Widnall: Yeah, absolutely. It isn't just young women; it's young women and their parents. I'm sure you've read the literature on cost of college. Parents have to think about whether spending $140,000 or more to get their daughter a degree in literature is really worth it. You have to think it through a bit. Why are you spending this money? What is it going to lead to? What are your ambitions? What are the economic opportunities? We just don't spend the money for things that are totally impractical.

Air transportation and space, it's going to be there. It's very exciting. I see a lot of students playing it safe. I've got a whole bunch of Air Force ROTC students as freshman advisees, and they are turning to other fields because they are a little concerned about aerospace. I think we have to work hard to make sure people really understand the benefits and the opportunities in aerospace.

AeroAstro: What concerns do you have?

Widnall: I think there are lots of things to worry about. Government support is something to worry about. I was watching

"American Experience." The thing that comes through in this show is the effect of government programs on advancements in both the economy and in research. I'm thinking specifically about activities during the Depression; we really put our boots on and got to work. We built Hoover Dam; we built Grand Coulee Dam. We pulled ourselves out by doing that. If you look back, you would say that WW II was a benefit because we started the aerospace industry, we revived our manufacturing, etc. If you looked at the US before WW II, and you looked at the US after WW II, the incredible amount of activity that WW II generated in science, technology, manufacturing, industrial base — all of that was amazing. The other night I watched ("American Experience's") "Silicon Valley." The thing that came through to me in that was the role of the military. The development of the Nike (missile) and all of that put enormous pressure on American industry to come up with devices that could satisfy the requirements of those advanced systems. I was stunned because I hadn't realized that. If the military had not been pushing, what would have happened? I don't know. They pushed, they needed materials that would go to high temperatures, etc. etc. So they pushed and pushed and pushed and ended up with the silicon chip, the integrated circuit, and all of that. It was just an amazing program.

AeroAstro: What do you think about the growth of online education?

Widnall: It's challenging. We don't know how to do it. I don't know what it's going to lead to. It's going to take a lot of faculty time away from personal interaction with students. I think that's clear. We may be able to develop some more effective approaches. That has yet to be demonstrated. I remember when computers were invented, people got very excited about online education. It has not proven to be an exciting opportunity. So we're in what you might call the "sixth wave" of the development of online education.

I'm very much for open courseware. I think that's really important. I'm very much for MIT being nonprofit in online education; that's a whole values thing. When Chuck Vest introduced OpenCourseWare, I thought it was really important that it was open, nonprofit. I said to Chuck, "If you treat this as a profit center for faculty and give them a share of the revenue, they're going to spend all their time trying to make money on these bits and pieces of things that we're charging for online." I've seen that happen at other universities.

I said, "I think it's really important to make this stuff free and let it develop naturally." And that's what happened. So we have a really solid base with open courseware and it gives us a really good platform to take the next step. There are things in open courseware that feed directly into edX or whatever you want to call it. Like Walter Lewin's lectures and things like that.

AeroAstro: Let's talk for a moment about your Air Force experience. I know President Clinton was the one who put you in that position. How did that come about?

Widnall: It's pretty straightforward. No, it's not that straightforward. I tell people it was the coming together of two strands of DNA. I had a relationship with the Air Force and the person who will take credit for that is a man named Hans Mark. Hans was the head of NASA Ames. Then he was the Associate Administrator of NASA, he was Under Secretary of the Air Force, and later he was Secretary of the Air Force. I met him at NASA Ames. I think he is probably one of these people that I really benefited from — people who took seriously the need to identify young women for mentorship and positions.

I had a presidential appointment to the Air Force Academy Board of Visitors as a civilian. The Air Force Academy Board of Visitors is composed of senators, congressmen, and citizens. I served two presidential terms. That was the beginning of my relationship with the Air Force in a serious way.

I had other relationships with the Air Force. I was Director of University Research in the Department of Transportation in 1974. The Under Secretary, John Barnam, and I became very close because the university research program had to work with all the assistant secretaries and the under-secretaries to get our program funded.

When John Barnam left DOT and I came back to MIT, he became chairman of what's called the Civil Reserve Air Fleet. It's the organization that interacts with the Air Force and the airline industry to organize aircraft that will be needed in a time of war. He asked me to become a member of that board. So, I was a member of the CRAF board, which worked with the Air Force to get charters lined up in case we needed all these airplanes. I got to know the four-star who was in charge of military airlift command, and a lot of other people. John had been Under Secretary of the Department of Transportation so I started knowing all these people, including the Air Force personnel and military airlift command. So, I had a substantial link with the Air Force. I knew all the superintendents of the Air Force Academy. I was on the board to choose two of the new Air Force Academy superintendents and two of the the new deans of the faculty. Now, that's one strand of DNA.

On July 4, 1993, President Bill Clinton announced Widnall's nomination as Secretary of the Air Force. The Senate confirmed her on August 5; she served as secretary for four years. (Courtesy Sheila Widnall)

On the other side, I was president of AeroAstroAS and the AeroAstroAS board. I got to know a man named David Hamburg, who was AeroAstroAS president. He was also president of the Institute of the Medicine. When David left the Institute of Medicine he became chairman of the Carnegie Corporation of New York. He asked me to be on his board. So, I was on the Carnegie Corporation board, I was vice chairman.

Now we're getting up to the election. The chairman of the Carnegie Corporation board is Warren Christopher who was tasked by Clinton to form the cabinet. I got a call from the Clinton administration early in the formation of the government and they said, "Do you want to come to Washington?" It was just some staff guy collecting information.

I said, "No, I really don't. I don't want to work for NASA. I don't want to be in the Office of the Secretary of Defense. I don't want to come to Washington."

Then, I get a call from David Hamburg who said, "Sheila. I've got this great idea. I've talked it over with the head of the Senate Armed Services Committee and the new Secretary of Defense that Clinton is going to appoint, and they all think it's a great idea."

I said, "Well, David, what great idea is that?"

He said, "We think you should be Secretary of the Air Force."

I said, "David, that is a terrific idea!"

When David got this ball rolling, I got another call from the White House and they said, "We called you earlier and you said you didn't want to come to Washington."

I said, "There's really only one job I want."

They said, "What's that?"

I said, "I'd like to be Secretary of the Air Force."

They said, "OK," and hung up.

That's how it started. What I mean is that there is one strand that's Air Force related, and another strand that's public policy, outside corporate boards, AeroAstroAS, science policy, science and government and all of that kind of stuff. Those two things come together. Hillary thought it was great to have a woman in this position. I mean no woman has ever done this job, even since. I'm the only woman who has ever done this job.

AeroAstro: You're legendary for having an incredible amount of energy. In addition to all your teaching, research, and public service, you manage to find time for rugged physical activity, like long-distance bicycle riding.

Widnall: You have to make time. With respect to the Air Force, it was a benefit. In other words, the Air Force had an emphasis on physical fitness. We actually had a cycling test that people had to pass to demonstrate physical fitness. I rode across Iowa in RAGBRAI four times with the Air Force; 500 miles. An Air Force team, about 150 Air Force people with matching uniforms, and we rode across Iowa. The media would interview us, and I would talk to high school teachers and, of course, so would the Air Force people, my team. A lot of these things were for visibility and working with the Air Force. The Air Force people who came with us were highly motivated and it was good publicity. It all fit together. When I went to an Air Force base in Turkey or Japan, I would get up early in the morning and go for a ride with the local Air Force people. I would ride with whatever group on the base made sense. I remember riding in New Zealand with a group of New Zealand people who were cyclists. We were visiting around the world and that was always part of what we did.

AeroAstro: One last area I would like to ask you about. This is the tenth anniversary of your appointment to the Columbia Space Shuttle Accident Investigation Board. What, in retrospect, are your thoughts about that?

Widnall: It's complicated. Yes, clearly it was emotional. But I would say that the intermediate level was more the whole issue of culture between NASA and the accident: the cultural predecessors of the accident; NASA's approach to safety. Starting from the technical level, we all know what happened.

But then you take the next step up and you're talking about safety, you're talking about risk, you're talking about risk analysis, risk management. You're talking about culture, talking about decision-making. Those are things that I call the next-level issues, which the board dealt with. Obviously the personal issues were devastating, but there wasn't anything that could be done at that point about that. The astronauts had been lost. So the question was to identify the deeper reasons why such an accident would occur and to make those reasons public.

One thing that was interesting about it was the defensiveness of NASA. We had a lot of meetings with NASA and there was a lot of pounding on the table. But we had a very strong board and because we were who we were, we always won. We insisted on having our own way, in spite of the fact that NASA didn't want us to be there; they didn't want us to be in charge; they didn't want us to investigate this area; they did not want us to conduct a test. They said, "We think you're just wasting money and we really don't want you to do this. We'll agree with you that the foam put a hole in the shuttle." But, as I say, we just pounded on the table, I mean literally pounded on the table. We had to remove some people from the NASA management chain, move them off. We didn't fire them, we just moved them off to a different part of the organization because we said they had been part of the management structure that led to the accident and there was no way in the world we were going to have to report to them or interact with them or have them influence the investigation. So there was a lot of real insistence on our part that we were in charge, and we were going to run this investigation. We had some very, very strong people, including me.

AeroAstro: So, what do you want to do next?

Widnall: That's an interesting question. At this point in my career I'm really enjoying teaching. Enjoying working with the undergraduates. I'm not expecting any enormous breakthroughs at this point. I'm at an age where I really ought to be thinking about retiring.

AeroAstro: Are you thinking about retiring?

Widnall: Yeah, sure. You have to think about retiring.

AeroAstro: I can't picture you retiring, just sitting in a chair or playing shuffleboard.

Widnall: No, I can't either. That's why I'm still uncertain about it.

AeroAstro: What would you like to do when you retire?

Widnall: I don't know. That's a big step. Whether I want to do more traveling or get involved with something on the outside. I don't know. That's an enormous step.

AeroAstro: It's hard to see you doing something other than engineering.

Widnall: Yes. It'd be a real change of lifestyle, and I'm not to a point where I can imagine doing that!

WILLIAM LITANT is the Aeronautics and Astronautics Department communications director. He may be reached at wlitant@mit.edu.

Eric Ducharme (AeroAstro SM '85, ScD '87) led development of General Electric's Evolution Series locomotive. The engine meets the EPA's strict new Tier 4 emissions standards, lowering particulate emissions from comparable past locomotives by 70 percent and NO_2 emissions by 76 percent. (General Electric)

AEROASTRO ALUMNI INTERVIEW:
ERIC DUCHARME, (SM '85, SCD '87) VP GLOBAL TECHNOLOGY, GE TRANSPORTATION

From the Gas Turbine Lab to global transportation technologies

AeroAstro: When did you become interested in aerospace engineering?

Ducharme: I grew up on Canadian Air Force bases across Canada and Europe and was fascinated and pumped-up anytime an airplane, especially a fighter jet, took off or flew by. I knew I wanted to be part of aviation from those early years. I've always had a curiosity of how things work and in creating things, so aeronautical engineering was a natural fit. I completed my undergraduate degree in mechanical engineering (with an aeronautics option) from McGill University in Montreal. Immediately after that, I enrolled at MIT for my graduate studies in Course 16.

AeroAstro: What did you do while in AeroAstro?

Ducharme: I was a graduate student in the Gas Turbine Lab from '83 thru '87, with Professor Ed Crawley as my advisor. My master's thesis project was focused on rotor dynamics (whirl) of cantilevered turbofans and was sponsored by NASA. My doctoral thesis, which was sponsored by GE Aviation, focused on the aeroelasticity of composite unducted fans (aka UDFs or propfans). I spent a lot of time testing in the Gas Turbine Lab compressor blowdown tunnel and in the Wright Brothers Wind Tunnel. These projects were particularly relevant to the jet engine industry, and the resulting technology developments helped pave the way for key innovations in commercial jet engines.

AeroAstro: What things particularly stand out about your time at MIT?

Ducharme: I loved the intellectually stimulating atmosphere, environment, and people. At MIT we tackle some of the world's biggest challenges in technology. I've sustained my ties to MIT, in that I serve as GE's university executive for MIT, responsible for fostering the MIT-GE relationship, including education and research collaboration and recruiting.

AeroAstro: What have you done since leaving MIT?

Ducharme: My work at MIT was collaborative with GE Aviation under the Industrial Liaison Program, so it was a natural follow-on for me to join the team at GE when I graduated. I started working on composite fan blade aeromechanics — that technology became an enabler for our success with large composite turbofan engines, such as the GE90 and the GEnx. Later, I moved from airfoil technology to engine systems design, where I led engine development programs such as the CFM56-7B and the GE90. Subsequently, I led engineering programs across all of GE's commercial jet engines. I've also worked at other GE businesses, including GE Transportation, where I led the development of the Evolution locomotive, and where I've returned to serve as the VP of Engineering & Technology. I also remain connected to the broader engineering profession, in that I serve as chairman of ASME's Industry Advisory Board. On a personal note, I've been fortunate to have a wonderful and supportive family. My wife Kerry and I have three adult children; they are all a huge part of my life.

AeroAstro: Tell us more about your current job.

Ducharme: My current role is vice president of engineering at GE Transportation, a business providing transportation and propulsion system solutions for customers in the rail, off-highway/mining vehicle, marine, and adjacent markets. We're big in diesel-electric freight locomotives and all the associated technologies: drivetrain, propulsion, energy storage, and communications and signaling. We have a global team of more than 1,600 engineers and will invest $600 million in technology over 2010-2011. It's been exciting and rewarding to help transform our business from one that was North American freight locomotive-centric, to a much broader global transportation business. A key technology challenge we're tackling now is meeting the new EPA and global emissions regulations for our diesel engines with solutions that drive customer value.

AeroAstro: What are your favorite aspects of your job?

Ducharme: I enjoy enabling the personal development of engineers and growing the broader capability of our technology team as we deliver new products and services to our customers. It's immensely satisfying to launch a winning new product that leads with technology (such as the GE90 & GEnx jet engines and the Evolution locomotive), or to have someone on your team grow and succeed at the next level.

AeroAstro: How did AeroAstro prepare you for your career?

Ducharme: My thesis projects were very much hands-on/applied and aligned with solving industry needs; that provided great initial conditions for launching my career. The AeroAstro focus on applying fundamentals and systems thinking has served me well. The fun we had on our AeroAstro intramural hockey team also highlighted the importance of teamwork and having fun with the people you work with. All these prepared me for my career in aircraft engines, as well as in transportation.

AeroAstro: What advice would you offer to high school students about considering aerospace engineering careers?

Ducharme: Aerospace engineering is immensely exciting and rewarding. There are many challenges yet to be solved in aerospace engineering and the caliber of people you will work with are second to none. If you're willing to apply yourself to the challenge — in high school, to prepare yourself, as well as in university to maximize the your learning and personal development — then great opportunities are out there. Besides that, aerospace is cool!

AeroAstro: What advice would you offer to current AeroAstro students to best position themselves for their careers?

Ducharme: It's important to take on relevant summer/Independent Activities Period internships, etc, to develop your skillset and your network. Get involved in student projects that are aligned with your career interests. Take full advantage of the many opportunities that AeroAstro offers. Also commit yourself to lifelong learning and development. What you know today is only a fraction of what you'll need for success throughout your career.

AeroAstro: How do you perceive current career opportunities for those who graduate with an AeroAstro undergrad degree?

Ducharme: I think the MIT AeroAstro focus on fundamentals, systems thinking, and teamwork, embodied in CDIO (Conceive-Design-Implement-Operate) framework, is exactly on target for a career in industry. The demographics of today's aerospace engineering population are scary; we stand to lose a huge percentage of our talent to retirement in the next 5-10 years, and that's a great opportunity for new graduates. While there may some future reduction in government-funded programs, the commercial aerospace industry is growing robustly.

AeroAstro: What do you like to do in your spare time?

Ducharme: I enjoy outdoor activities, especially hiking, fishing, kayaking and skiing. Doing that with family and friends is great.

AeroAstro: Anything else you'd like to tell us?

Ducharme: MIT AeroAstro is a world-class education and research school that I feel privileged to be part of. Best wishes for continued success and technology leadership.

LAB REPORT:

A 2012-2013 review of Aeronautics and Astronautics Department laboratories

Information provided by the research laboratories and centers.

Spending the summer of 2013 working as an Undergraduate Research Opportunities Program student, AeroAstro junior Peter Williams prepares a new 1:11 model of the D-8 aircraft for testing in the Wright Brothers Wind Tunnel. Created by an MIT-led team, the D-8 is designed to be more efficient, quieter, and cleaner than contemporary commercial aircraft. (William Litant)

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

The Aerospace Computational Design Laboratory's mission is the advancement and application of computational engineering for the design, optimization, and control of aerospace and other complex systems. ACDL research addresses a comprehensive range of topics including advanced computational fluid dynamics and mechanics, uncertainty quantification, data assimilation and statistical inference, surrogate and reduced modeling, and simulation-based design techniques.

Advanced simulation methods developed by ACDL researchers facilitate the understanding and prediction of physical phenomena in aerospace systems and other applications. A long-standing interest of the lab has been the advancement of computational fluid dynamics for complex three-dimensional flows, enabling significant reductions in time from geometry to solution. Specific research interests include aerodynamics, aeroacoustics, flow control, fluid structure interactions, hypersonic flows, high-order methods, multilevel solution techniques, large eddy simulation, and scientific visualization. Research interests also extend to chemical kinetics, transport-chemistry interactions, and other reacting flow phenomena important for energy conversion and propulsion.

The ACDL's efforts in *uncertainty quantification* aim to endow computational predictions with quantitative measures of confidence and reliability, while addressing broad underlying challenges of model validation. Complementary efforts in *statistical inference* and *data assimilation* are aimed at estimating and improving physical models and predictions by conditioning on observational data. Current research has developed effective methods for error estimation, solution adaptivity, sensitivity analysis, uncertainty propagation and the solution of stochastic differential equations, the solution of large-scale statistical inverse problems, nonlinear filtering in partial differential equations, and optimal experimental design. Applications range from aerospace vehicle design to large-scale geophysical problems and subsurface modeling.

ACDL research in *simulation-based design* and *control* is aimed at developing methods to support better decision-making in aerospace and other complex systems, with application to conceptual, preliminary, and detailed design. Our recent efforts have yielded effective approaches to PDE-constrained optimization, real time simulation and optimization of systems governed by PDEs, multiscale and multi-fidelity optimization, model order reduction, geometry management, and fidelity management. ACDL applies these methodologies to aircraft design and to the development of tools for assessing aviation environmental impact.

ACDL faculty include Youssef Marzouk (director), David Darmofal, Mark Drela, Jaime Peraire, Qiqi Wang, and Karen Willcox. Research staff include Doug Allaire, Robert Haimes, Tarek Moselhy, and Cuong Nguyen.

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

AEROSPACE CONTROLS LABORATORY

The Aerospace Controls Laboratory researches 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, mission planning for unmanned aerial vehicles, sensor network design, and robust, adaptive, and nonlinear control. A key aspect of ACL is RAVEN (Real-time indoor Autonomous Vehicle test ENvironment), a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, and robust coordination algorithms for multiple vehicles. Recent research includes the following:

Robust Planning in Uncertain Environments: ACL developed consensus-based bundle algorithı as a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multi-agent missions. Aside from extensions to task time-windows, coupled agent constraints, asynchronous communications, and limited network, CBBA has been validated in real-time flight test experiments. ACL has also extended its development of chance-constrained rapidly-exploring random trees (CC-RRT), a robust planning algorithm to identify probabilistically feasible trajectories, to new aerospace domains. For instance, in work with Professor Sertac Karaman, ACL recently developed CC-RRT*, which uses the asymptotic optimality principles of RRT* to solve robust pursuit-evasion problems. ACL is also involved in a multi-year Draper URAD on precision landing of guided parafoils, with robustness to large and dynamic wind environments. Finally, ACL is participating in a multi-year MURI focused on enabling decentralized planning algorithms under uncertainty. Ongoing ACL research has demonstrated that the use of flexible non-parametric Bayesian models for learning models of uncertain environment can greatly improve planning performance.

UAV Mission Technologies: ACL has developed a novel hovering vehicle concept capable of agile, acrobatic maneuvers in cluttered indoor spaces. The vehicle is a quadrotor whose rotor tilt angles can be actuated, enabling upside-down hovering flight with appropriate control algorithms. Additionally, as part of research on long-duration UAV mission planning, ACL has constructed an autonomous recharge platform, capable of autonomous battery replacement and recharging for small UAVs. This capability allows ACL to demonstrate complex, multi-agent missions lasting for several hours.

Information-Gathering Networks: Recent ACL research has addressed maximizing information gathering in complex dynamic environments, through quantifying the value of information and the use of mobile sensing agents. The primary challenge in such planning is the computational complexity, due to both the large size of the information space and the cost of propagating sensing data into the future. ACL researchers created adaptive efficient distributed sensing in which each sensor propagates only high value information, reducing the network load and improving scalability. Recently-developed algorithms embed information planning within RRTs to quickly identify safe information-gathering trajectories for teams of sensing agents, subject to arbitrary constraints and sensor models.

Task Identification and Decision-Making: Markov Decision Processes are a natural framework for formulating many decision problems of interest, ACL has identified approximate solution techniques which can utilize this framework while overcoming the curse of dimensionality typically encountered for exact solutions. By exploiting flexible, kernel-based cost approximation architectures, ACL's Bellman Residual Minimization algorithm computes an approximate policy by minimizing the error incurred in solving Bellman's equation over sampled states. For online systems, ACL introduced the incremental Feature Dependency Discovery (iFDD) algorithm that expands the representation in areas where the sampled Bellman errors persist. Recently, this algorithm has been extended to the offline setting where it has been shown to be effective on previously collected datasets. ACL has also developed a Bayesian Nonparametric Inverse Reinforcement Learning algorithm for identifying tasks from traces of user behavior. This technique allows a user to "teach" a task to a learning agent through natural demonstrations. Finally, ACL has enabled fast, real-time learning in combination with cooperative planning in uncertain and risky environments, while maintaining probabilistic safety guarantees for the overall system behavior.

ACL faculty are Jonathan How and Steven Hall.

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

AEROSPACE ROBOTICS AND EMBEDDED SYSTEMS GROUP

The Aerospace Robotics and Embedded Systems group's mission is the development of theoretical foundations and practical algorithms for real-time control of large-scale systems of vehicles and mobile robots. Application examples range from UAVs and autonomous cars, to air traffic control, and urban mobility. The group researches advanced algorithmic approaches to control high-dimensional, fast, and uncertain dynamical systems subject to stringent safety requirements in a rapidly changing environment. An emphasis is placed on the development of rigorous analysis, synthesis, and verification tools to ensure the correctness of the design. The research approach combines expertise in control theory, robotics, optimization, queuing theory and stochastic systems, with randomized and distributed algorithms, formal languages, machine learning, and game theory.

Current research areas include the following.

Real-time motion planning and control: The group is developing state-of-the art algorithms for real-time control of highly maneuverable aircraft, spacecraft, and ground vehicles. Focus areas include optimality and robustness, as well as provable safety and correctness with respect to temporal-logic specifications (e.g., rules of the road, rules of engagement). Current projects include high-speed flight in cluttered environments, and high-speed offroad driving.

Multi-agent systems: Large, heterogeneous groups of mobile vehicles, such as UAVs and UGVs, are increasingly being used to address complex missions for many applications, ranging from national security to environmental monitoring. An additional emphasis in this work is scalability: namely, our objective is not only the design of distributed algorithms to ensure provably efficient and safe execution of the assigned tasks, but also to understand exactly how the collective performance and implementation complexity scale as the group's size and composition change.

Transportation networks: Traffic congestion, and extreme sensitivity to, e.g., environmental disruptions, is a well-known effect of increasing access to transportation. As infrastructure development saturates, new approaches are necessary to increase the safety, efficiency, and environmental sustainability of transportation networks. The group's research in this area concentrates on the exploitation of real-time information availability through wireless communications among vehicles, and with existing infrastructure, to achieve this goal.

Emilio Frazzoli directs the Aerospace Robotics and Embedded Systems group.

Visit the Aerospace Robotics and Embedded Systems group at http://ares.lids.mit.edu

AUTONOMOUS SYSTEMS LABORATORY

The Autonomous Systems Laboratory is a virtual lab led by Professors Brian Williams and Nicholas Roy. Williams 'group, the Model-based Embedded and Robotics (MERS) group, and Roy's Robust Robotics Group are part of the Computer Science and Artificial Intelligence Lab. ALS work is focused on developing autonomous aerospace vehicles and robotic systems.

ASL-developed systems are commanded at a high-level in terms of mission goals. The systems execute these missions robustly by constantly estimating their state relative to the world, and by continuously adapting their plan of action, based on engineering and world models.

Below are several recent demonstrations.

- Operating autonomous vehicles to maximize utility in an uncertainty environment, while operating within acceptable levels of risk. Autonomous underwater vehicles enable scientists to explore previously uncharted portions of the ocean, by autonomously performing science missions of up to 20 hours in length, without the need for human intervention. Performing these extended missions can be a risky endeavor. Researchers have developed robust, chance-constraint planning algorithms that automatically navigate vehicles to achieve user specified science goals, while operating within risk levels specified by the users. (Video at http://www.csail.mit.edu/videoarchive/research/robo/auv-planning)
- Another demonstration involves human-robot interaction between a robotic air taxi and a passenger. The task is for the autonomous vehicle to help the passenger rethink goals when they no longer can be met. Companies like the MIT spinoff Terrafugia offer vehicles that can fly between local airports and can travel on local roads. To operate these innovative vehicles, one must be trained as a certified pilot, thus limiting the population that can benefit from this innovative concept.
- In collaboration with Boeing, MERS has demonstrated in simulation the concept of an autonomous personal air vehicle, called PT, in which the passenger interacts with the vehicle in the same manner that they interact today with a taxi driver. (Video at http://www.csail.mit.edu/videoarchive/research/robo/personal-aerial-transportation.)
- A third demonstration involves human-robot interaction between an astronaut and the Athlete Lunar Rover. MERS has developed methods for controlling walking machines, guided by qualitative "snapshots" of walking gait patterns. These control systems achieve robust walking over difficult terrain by embodying many aspects of a human's ability to restore balance after stumbling, such as adjusting ankle support, moving free limbs, and adjusting foot placement. Members of the MERS group applied generalizations of these control concepts to control the JPL Athlete robot, a six-legged/wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms. (Video at http://www.csail.mit.edu/videoarchive/research/robo/athlete-mers.)

ASL faculty are Brian Williams and Nicholas Roy. Visit the Model-based Embedded Systems at mers.csail.mit.edu and the Robust Robotics Group at http://groups.csail.mit.edu/rrg/

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

The Communications and Networking Research Group's primary goal is 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 communication networks and systems, with application to satellite, wireless, and optical systems. In recent years, the group has been developing efficient network control algorithms for heterogeneous wireless networks. Existing wireless networks are almost exclusively confined to single hop access, as provided by cellular telephony or wireless LANs. While multi-hop wireless networks can be deployed, current protocols typically result in extremely poor performance for even moderate sized networks. Wireless Mesh Networks have emerged as a solution for providing last-mile Internet access. However, hindering their success is our relative lack of understanding of how to effectively control wireless networks, especially in the context of advanced physical layer models, realistic models for channel interference, distributed operations, and interface with the wired infrastructure (e.g., internet). CNRG has been developing effective and practical network control algorithms that make efficient use of wireless resources through the joint design of topology adaptation, network layer routing, link layer scheduling, and physical layer power, channel, and rate control.

Robust network design is another exciting area of recent pioneering research by the group. In particular, the group has been developing a new paradigm for the design of highly robust networks that can survive a massive disruption that may result from natural disasters or intentional attack. The work examines the impact of large-scale failures on network survivability and design, with a focus on interdependencies between different networked infrastructures, such as telecommunication networks, social networks, and the power grid. 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/

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 60 years. The GTL's mission is to advance the state-of-the-art in fluid machinery for power and propulsion. The research is focused on advanced propulsion systems, energy conversion and power, with activities in computational, theoretical, and experimental study of: loss mechanisms and unsteady flows in fluid machinery, dynamic behavior and stability of compression systems, instrumentation and diagnostics, advanced centrifugal compressors and pumps for energy conversion, gas turbine engine and fluid machinery noise reduction and aero-acoustics, novel aircraft and propulsion system concepts for reduced environmental impact.

Examples of current research projects include: a unified approach for vaned diffuser design in advanced centrifugal compressors, a methodology for centrifugal compressor stability prediction, improved performance return channel design for multistage centrifugal compressors, investigation of real gas effects in supercritical CO_2 compression systems, modeling instabilities in high-pressure pumping systems, aeromechanic response in a high performance centrifugal compressor stage, ported shroud operation in turbochargers, manifestation of forced response in a high performance centrifugal compressor stage for aerospace applications, return channel design optimization using adjoint method for multistage centrifugal compressors, a two engine integrated propulsion system, inlet swirl distortion effects on the generation and propagation of fan rotor shock noise, propulsion system integration and noise assessment of a hybrid wing-body aircraft, fan-inlet integration for low fan pressure ratio propulsors, aerodynamics and heat transfer in gas turbine tip shroud cavity flows, secondary air interactions with main flow in axial turbines, compressor aerodynamics in large industrial gas turbines for power generation, turbine tip clearance loss mechanisms, flow and heat transfer in modern turbine rim seal cavities, and modeling cavitation instabilities in rocket engine turbopumps.

Faculty and research staff include: Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Arthur Huang, Claudio Lettieri, Zoltan Spakovszky (director), Choon Tan, and Alejandra Uranga.

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, human performance modeling with hidden Markov models, collaborative human-computer decision making in time-pressured scenarios (for both individuals and teams), human supervisory control of multiple unmanned vehicles, and designing displays that reduce training time. Lab equipment includes an experimental testbed for future command and control decision support systems, intended to aid in the development of human-computer interface 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. Current research sponsors include the Office of Naval Research, the U.S. Army, Lincoln Laboratory, Boeing, the Air Force Research Laboratory, the Air Force Office of Scientific Research, Alstom, and the Nuclear Regulatory Commission.

HAL faculty include Mary L. 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 AVIATION AND THE ENVIRONMENT

The Laboratory for Aviation and the Environment was founded 1992 under the name of the "Aero-Environmental Research Laboratory" by Ian A. Waitz, now Dean of the MIT School of Engineering. One of the defining challenges of the aviation industry is to address its environmental impacts in terms of noise, air quality and climate change. The goal of the Laboratory is to align the trajectory of aerospace technology and policy development with the need to mitigate these impacts. It does so by increasing the understanding the environmental effects of aviation, by developing and assessing fuel-based, operational and technological mitigation approaches and by disseminating knowledge and tools. The Laboratory also contributes to cognate areas of inquiry in aerospace, energy and the environment

LAE researchers are analyzing environmental impacts and developing research tools that provide rigorous guidance to policy-makers who must decide among alternatives when addressing aviation's environmental impact. The MIT researchers collaborate with international teams in developing aircraft-level and aviation system level tools to assess the costs and benefits of different policies and mitigation options.

A current focus at LAE is on studying the environmental sustainability of alternative aviation fuels from biomass or natural gas and coal. This research includes both drop-in fuel options, which can be used with existing aircraft engines and fuel infrastructure, as well as non-drop-in options such as liquefied natural gas, which would require modifications to aircrafts and infrastructure. Environmental metrics considered include life-cycle greenhouse gas emissions, land requirements and water consumption. Researchers at LAE are also estimating trade-offs among different metrics and usages to better understand the full consequences of introducing a certain alternative fuel into the aviation system.

LAE has released a global emissions dataset for civil aviation emissions, which represents the most current estimate of emissions publicly available. It is widely used by researchers worldwide, in areas including atmospheric modeling and aviation and the environment.

Other recent work investigates public health and climate impacts of ultra low sulfur jet fuel and air quality impacts of increasing airport capacity in the United Kingdom. LAE-reports and publications can be accessed at http://lae.mit.edu.

The laboratory is also operational headquarter of the Partnership for Air Transportation Noise and Emissions Reduction, an FAA Center of Excellence sponsored by the FAA, NASA, Transport Canada, the US Department of Defense, and the Environmental Protection Agency. PARTNER combines the talents of 12 universities, five government agencies, and more than 50 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups. The PARTNER leadership is based at LAE with Ian Waitz as PARTNER director and Steven Barrett as PARTNER associate director.

LAE faculty includes Steven Barrett (director), Hamsa Balakrishnan, John Hansman, Ian Waitz and Karen Willcox. Robert Malina is the lab's associate director.

Visit LAE at http://lae.mit.edu.

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems at MIT is an interdepartmental research center committed to advancing research and education in the analytical information and decision sciences, specifically: systems and control, communications and networks, and inference and statistical data processing.

Dating to 1939, LIDS has been at the forefront of major methodological developments, relevant to diverse areas of national and worldwide importance, such as telecommunications, information technology, the automotive industry, energy, defense, and human health. Building on past innovation and bolstered by a collaborative atmosphere, LIDS members continue to make breakthroughs that cut across traditional boundaries.

Members of the LIDS community share a common approach to solving problems and recognize the fundamental role that mathematics, physics, and computation play in their research. Their pursuits are strengthened by the laboratory's affiliations with colleagues across MIT and throughout the world, as well as with leading industrial and government organizations.

LIDS is based in MIT's Stata Center, a dynamic space that promotes a high level of interaction within the lab and with the larger MIT community. Currently 17 faculty are affiliated with the laboratory, including Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

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

THE LEARNING LABORATORY

The AeroAstro Learning Laboratory, located in Building 33, promotes student learning by providing an environment for hands-on activities that span our conceive-design-implement-operate educational paradigm.

The Learning Lab comprises four main areas:

Robert C. Seamans Jr. Laboratory. The Seamans Laboratory occupies the first floor. It includes:

» *The Concept Forum* — a multipurpose room for meetings, presentations, lectures, videoconferences and collaboration, distance learning, and informal social functions. In the Forum, students work together to develop multidisciplinary concepts, and learn about program reviews and management.

» *Al Shaw Student Lounge* — a large, open space for social interaction and operations.

Arthur and Linda Gelb Laboratory. Located in the building's lower level, the 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 starting as first-year students and continuing through the last year. The Gelb facilities are designed to foster teamwork with a variety of resources to meet the needs of curricular and extra-curricular projects.

Gerhard Neumann Hangar. The Gerhard Neumann Hangar is a high bay space with an arching roof. This space lets students work on large-scale projects that take considerable floor and table space. Typical of these projects are planetary rovers, autonomous vehicles, and re-entry impact experiments. The structure also houses low-speed and supersonic wind tunnels. A balcony-like mezzanine level is used for multi-semester engineering projects, such as the experimental three-term senior capstone course, and is outfitted with a number of flight simulator computer stations.

Digital Design Studio. The Digital Design Studio, located on the second floor, is a large room with multiple computer stations arranged around reconfigurable conference tables. Here, students conduct engineering evaluations and design work, and exchange databases as system and subsystem trades are conducted during the development cycle. The room is equipped with information technologies that facilitate teaching and learning in a team-based environment. Adjacent and networked to the main Design Studio are two smaller design rooms: the AA Department Design Room, and the Arthur W. Vogeley Design Room. These rooms are reserved for the use of individual design teams and for record storage. The department's IT systems administrator is positioned for convenient assistance in an office adjacent to the Design Center.

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory addresses human-vehicle and human-robotic system safety and effectiveness by improving understanding of human physiological and cognitive capabilities. MVL develops countermeasures and display designs to aid pilots, astronauts, and others. Research is interdisciplinary, and uses techniques from manual and supervisory control, signal processing, estimation, robotics, 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 developed experiments for the International Space Station.

Space projects focus on advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity, mathematical models for human spatial disorientation accident analysis, artificial intelligence, and space telerobotics training. New major projects include a collaborative study with Draper laboratory on manual and supervisory control of lunar/planetary landings, and a study of fatigue effects on space teleoperation performance, in collaboration with colleagues at the Brigham and Women's Hospital. Non-aerospace projects include performance and fatigue effects in locomotive engineers, and advanced helmet designs for brain protection in sports and against explosive blasts. A new initiative with Russian colleagues, under the umbrella of the MIT/Skolkovo initiative, emphasizes innovative solutions to the protection and performance enhancement of astronauts during space exploration. MVL projects include the use of a short radius centrifuge as a countermeasure, development of a g-loading suit to maintain muscle and bone strength, and the logistics of resupply and mission support.

MVL has five faculty and 20 affiliated graduate students. Research sponsors include NASA, the National Space Biomedical Research 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. The laboratory also collaborates with the Volpe Transportation Research Center, and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

MVL faculty include Charles Oman (director), Jeffrey Hoffman, Dava Newman, Laurence Young, and Julie Shah. They teach subjects in human factors engineering, space systems engineering, real-time systems and software, 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 HST Graduate Program in Bioastronautics (Young), the Massachusetts Space Grant Consortium (Hoffman), NSBRI Sensory-Motor Adaptation Team (Oman), the MIT-Volpe Program in Transportation Human Factors (Oman), and the MIT Portugal Program's Bioengineering Systems focus area (Newman).

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

NECSTLAB

The necstlab (pronounced "next lab") research group explores new concepts in engineered materials and structures. The group's mission is to lead the advancement and application of new knowledge at the forefront of materials and structures understanding, with research contributions in both science and engineering. Applications of interest include enhanced (aerospace) advanced composites, multifunctional attributes of structures such as damage sensing, and also microfabricated (MEMS) topics. A significant effort over the past decade has been to use nanoscale materials to enhance performance of advanced aerospace materials and their structures through the industry supported NECST Consortium.

The necstlab group has interests that span fundamental materials synthesis questions through to structural applications of both hybrid and traditional materials. This includes longstanding projects in MEMS and now bioNEMS/MEMS. While not all-encompassing, much of the group's work supports the efforts of the NECST Consortium, an aerospace industry-supported research initiative that seeks to develop the underlying understanding to create enhanced-performance advanced composites using nanotechnology. Beyond the NECST Consortium Members, necstlab research is supported by industry, AFOSR, ARO, NASA, NIST, NSF, ONR, and others.

The necstlab maintains collaborations around the MIT campus, particularly with faculty in the departments of Mechanical Engineering, Materials Science and Engineering, and Chemical Engineering, and MIT labs and centers including the Institute for Soldier Nanotechnologies, Materials Processing Center, Center for Materials Science and Engineering, and the Microsystems Technology Laboratory, as well as Harvard's Center for Nanoscale Systems. Important to the contributions of the necstlab are collaborations with leading research groups from around the world through formal and informal collaborations.

Example past and current research projects include:

- BioNEMS materials design and implementation in microfluidics
- buckling mechanics
- carbon nanostructure synthesis from non-traditional catalysts
- continuous growth of aligned carbon nanotubes
- electroactive nanoengineered actuator/sensor architectures focusing on ion transport
- nanoengineered (hybrid) composite architectures for laminate-level mechanical performance improvement
- multifunctional properties including damage sensing and detection
- manufacturing
- polymer nanocomposite mechanics and electrical and thermal transport
- Si MEMS devices including piezoelectric energy harvesters, microfabricated solid oxide fuel cells, stress characterization, and 3D MEMS
- VACNT characterization and physical properties

necstlab faculty include Brian L. Wardle (director), John Dugundji (emeritus), and visitors Alexandre Ferreira Da Silva, Antonio Miravete, and Desiree Plata

Visit necstlab at
http://web.mit.edu/dept/aeroastro/labs/necstlab/index.shtml

THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for AiR Transportation Noise and Emissions Reduction is an MIT-led FAA Center of Excellence sponsored by the FAA, NASA, Transport Canada, the US Department of Defense, and the Environmental Protection Agency. PARTNER research addresses environmental challenges facing aviation through analyzing community noise and emission impacts on climate and air quality. PARTNER also studies a range of environmental impact potential mitigation options including aircraft technologies, fuels, operational procedures, and policies. PARTNER combines the talents of 12 universities, five government agencies, and more than 50 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups.

MIT's most prominent research role within PARTNER is in analyzing environmental impacts and 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 mitigation options.

Other PARTNER initiatives in which MIT participates include estimating the lifecycle impacts of alternative fuels for aircraft, studies of aircraft particulate matter microphysics and chemistry, and economic analysis of policies. PARTNER collaborators' most recent reports include "Market Cost of Renewable Jet Fuel Adoption in the United States," "CO_2 Emission Metrics for Commercial Aircraft Certification: A National Airspace System Perspective," and "Assessment of Windows on Noise Intrusion, Energy Efficiency, and Indoor Air Quality for Residential Buildings near Airports." In addition, MIT PARTNER researchers have contributed to recently published reports and papers on such topics as traditional and alternative fuel use, aircraft emissions, and emissions trading.

PARTNER reports may be accessed at http://partner.mit.edu/reports-papers

PARTNER MIT personnel include Ian Waitz (director), Steven Barrett (associate director), Hamsa Balakrishnan, John Hansman, Karen Willcox, William Litant (communications director), Jennifer Leith (program coordinator), Helen Halaris (event coordinator), and 15-20 graduate students and post docs.

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

SPACE PROPULSION LABORATORY

The Space Propulsion Laboratory studies and develops systems for increasing performance and reducing costs of space propulsion and related technologies. 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. These efficient engines 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 plasma thrusters and plumes, and their interaction with spacecraft, numerical and experimental models of magnetic cusped thrusters, and space electrodynamic tethers, including their use as antennas for launching electromagnetic waves to remove high-energy particles from earth's Van Allen radiation belts. SPL students also work on ultra-fast (nanosecond) high voltage discharges to trigger combustion reactions and eventually reduce aircraft engine pollution. SPL also has a significant role in designing and building micropropulsion electrospray thrusters. In addition to providing efficient propulsion for very small satellites in the 1 kg category (such as CubeSats), such engines will enable distributed propulsion for the control of large space structures, like deformable mirrors and apertures. SPL facilities include a supercomputer cluster where plasma and molecular dynamics codes are routinely executed and a state-of-the-art laboratory including three vacuum chambers, clean room environment benches, electron microscope and electronic diagnostic tools to support ongoing research efforts.

Manuel Martinez-Sanchez directed the SPL through April 2013, at which time he passed the directorship to Paulo Lozano.

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 the exploration and development of space. The 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 leading the AeroAstro efforts on student-built small satellites. Research encompasses an array of topics that 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.

Several SSL initiatives study the development of formation flight technology. The Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) facility is used to develop proximity satellite operations such as inspection, cluster aggregation, collision avoidance and docking. The SPHERES facility consists of three satellites 20 centimeters in diameter that have flown inside the International Space Station since May 2006. In 2009, the SSL expanded the uses of SPHERES to include STEM outreach through an exciting program called Zero Robotics, which engages high school students in a competition aboard the ISS using SPHERES (http://www.zerorobotics.org/). In December 2010, ten students from two Idaho schools came to MIT and saw their algorithms compete against each other in a live feed from the ISS. Since then, Zero Robotics has been expanded to include middle school programs as well as a competition in Europe. In 2012, 96 teams from the United States and 47 teams from Europe competed.

In October 2012, the SPHERES facility on the ISS was expanded to include vision-based navigation through the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) program, which has already begun testing. VERTIGO will be used to develop vision-based navigation and mapping algorithms through a stereo camera system and an upgraded processor. In the summer of 2013, the University of Maryland Space Power and Propulsion Laboratory, Aurora Flight Sciences, and the SSL will again upgrade the SPHERES facility to include the Resonant Inductive Near-Field Generation System (RINGS), which will be used to test electromagnetic formation flight and wireless power transfer through a pair of tuned resonant coils that generate a time varying magnetic field. Also in 2013, the SSL is partnering with the Naval Research Laboratory to design robotic arms that will be incorporated into the SPHERES facility and with the Jet Propulsion Laboratory (JPL) and Aurora Flight Sciences for work on the Defense Advanced Research Projects Agency (DARPA) Phoenix program, which is developing the SPHERES facility to be used as a testbed for servicing and assembly missions.

The Wavefront Control Laboratory (WCL) develops nanosatellites, instruments, and algorithms that allow us to explore both our Earth and other worlds from space. WCL demonstrates wavefront control using MEMS deformable mirrors, Shack-Hartmann wavefront sensors, and liquid crystal spatial light modulators. Wavefront control systems are needed for applications such as space-based direct imaging of exoplanets (planets around other stars), laser communication systems (to improve bit error rate), and imaging systems (to correct for atmospheric turbulence or aberrations caused by the imaging system optics). WCL also uses radio-frequency waves to study the atmosphere and ionosphere of Earth and other Solar System planets with techniques such as radio occultation and microwave radiometry, and is building a 3U dual-spinning CubeSat hosting a 1U passive microwave radiometer for MIT Lincoln Laboratory, called the Microsized Microwave Atmospheric Satellite (MicroMAS). In addition, WCL collaborates with commercial satellite companies to investigate the connection between on-orbit component anomalies and space weather for geostationary communications spacecraft. (http://web.mit.edu/cahoylab).

The SSL is also developing nano-satellites to advance and mature innovative instrumentation and spacecraft bus designs for remote sensing missions. Examples include a dual-spinning 3U CubeSat to host a passive microwave radiometer (Microsized Microwave Atmospheric Satellite, MicroMAS, in collaboration with MIT Lincoln Laboratory), a cluster flight of three 3U CubeSats equipped with electrospray microthrusters (in collaboration with MIT AeroAstro's Space Propulsion Lab and Aurora Flight Sciences) called MotherCube, and a 3U Cubesat for transit detection of Earth-like planets around the nearest, brightest stars (in collaboration with MIT's EAPS Department and Draper) called ExoplanetSat. Also under development is TERSat (Trapped Energetic Radiation Satellite) for precipitation of energetic particles from the radiation belts, previously under the Air Force's University Nano-satellite Program (in collaboration with MIT AeroAstro's Space Propulsion Laboratory).

The SSL is also designing REXIS (REgolith X-ray Imaging Spectrometer), an instrument on NASA's OSIRIS-Rex asteroid sample return mission launching in 2016. REXIS uses charged-coupled detectors as an x-ray spectrometer to characterize the surface of asteroid 1999 RQ36. The project, which has included the work of over 50 undergraduate and graduate students, is successfully through its Preliminary Design Review and working towards its Critical Design Review sometime next year.

The SSL continues to lead the development of methodologies and tools for space logistics. Jointly with Aurora Flight Sciences, the SSL is developing prototypes for automated asset tracking and management systems for the ISS based on radio frequency identification technology. Together with JPL, the 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.

SSL personnel include David W. Miller (director), Kerri Cahoy, Olivier de Weck, Jeffrey Hoffman, Manuel Martinez-Sanchez, Paulo Lozano, Sara Seager, Alvar Saenz-Otero, Rebecca Masterson, Steve Ulrich, Alessandra Babuscia, Paul Bauer (research specialist), Jori Barabino (fiscal officer), and Marilyn E. Good (administrative assistant).

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

SYSTEM ENGINEERING RESEARCH LAB

The increasingly complex systems we are building today enable us to accomplish tasks that were previously difficult or impossible. At the same time, they have changed the nature of accidents and increased the potential to harm not only life today but also future generations. Traditional system safety engineering approaches, which started in the missile defense systems of the 1950s, are being challenged by the introduction of new technology and the increasing complexity of the systems we are attempting to build. Software is changing the causes of accidents and the humans operating these systems have a much more difficult job than simply following pre-defined procedures. We can no longer effectively separate engineering design from human factors and from the social and organizational system in which our systems are designed and operated.

The System Engineering Research Lab's goal is to create tools and processes that will allow us to engineer a safer world. Engineering safer systems requires multi-disciplinary and collaborative research based on sound system engineering principles, that is, it requires a holistic systems approach. LSSR has participants from multiple engineering disciplines and MIT schools as well as collaborators at other universities and in other countries. Students are working on safety in aviation (aircraft and air transportation systems), spacecraft, medical devices and healthcare, automobiles, railroads, nuclear power, defense systems, energy, and large manufacturing/process facilities. Cross-discipline topics include:

- hazard analysis
- accident causality analysis and accident investigation
- safety-guided design
- human factors and safety
- integrating safety into the system engineering process

- identifying leading indicators of increasing risk
- certification, regulation, and standards
- the role of culture, social, and legal systems on safety
- managing and operating safety-critical systems

The System Engineering Research Lab is directed by Nancy Leveson.

Visit the System Engineering Research Lab at
http://sunnyday.mit.edu/safety.html

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 advanced materials systems development and use in various advanced structural applications and devices.

TELAMS 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. Thus, the research interests and ongoing work in the laboratory represent a diverse and growing set of areas and associations. Areas of interest include:

- composite tubular structural and laminate failures
- MEMS-scale mechanical energy harvesting modeling, design, and testing
- MEMS device modeling and testing, including bioNEMS/MEMS
- structural health monitoring system development and durability assessment
- 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. 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 microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization. This includes ties to ability for computer microtomography.

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 materials 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. 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. Lagacé, John Dugundji (emeritus), and visitor Antonio Miravete.

Visit the Technology Laboratory for Advanced Materials and Structures at http://web.mit.edu/telams/

WIRELESS COMMUNICATION AND NETWORK SCIENCES GROUP

The Wireless Communication and Network Sciences Group is involved in multidisciplinary research that encompasses developing fundamental theories, designing algorithms, and conducting experiments for a broad range of real-world problems. Its current research topics include location-aware networks, network synchronization, aggregate interference, intrinsically-secure networks, time-varying channels, multiple antenna systems, ultra-wide bandwidth systems, optical transmission systems, and space communications systems. Details of a few specific projects are given below.

The group is working on location-aware networks in GPS-denied environments, which provide highly accurate and robust positioning capabilities for military and commercial aerospace networks. It has developed a foundation for the design and analysis of large-scale location-aware networks from the perspective of theory, algorithms, and experimentation. This includes derivation of performance bounds for cooperative localization, development of a geometric interpretation for these bounds, and the design of practical, near-optimal cooperative localization algorithms. It is currently validating the algorithms in a realistic network environment through experimentation in the lab.

The lab has been engaged in the development of a state-of-the-art apparatus that enables automated channel measurements. The apparatus makes use of a vector network analyzer and two vertically polarized, omni-directional wideband antennas to measure wireless channels over a range of 2–18 GHz. It is unique in that extremely wide bandwidth data, more than twice the bandwidth of conventional ultra-wideband systems, can be captured with high-precision positioning capabilities. Data collected with this apparatus facilitates the efficient and accurate experimental validation of proposed theories and enables the development of realistic wideband channel models. Work is underway to analyze the vast amounts of data collected during an extensive measurement campaign that was completed in early 2009.

Lab students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for guidance, navigation, and control of unmanned aerial vehicle networks. The framework they have developed introduces the notion of a secure communications graph, which captures the information-theoretically secure links that can be established in a wireless network. They have characterized the s-graph in terms of local and global connectivity, as well as the secrecy capacity of connections. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

To advocate outreach and diversity, the group is committed to attracting undergraduates and underrepresented minorities, giving them exposure to theoretical and experimental research at all levels. For example, the group has a strong track record for hosting students from both the Undergraduate Research Opportunities Program and the MIT Summer Research Program (MSRP). Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and Ferrara in Italy, University of Lund in Sweden, University of Oulu in Finland, National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Moe Win directs the Wireless Communication and Network Sciences Group.

Visit the Wireless Communication and Network Sciences Group at http://wgroup.lids.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.

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WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

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AEROASTRO #10

This issue marks the 10th anniversary of AeroAstro magazine. Behind the great stories of people and technology, there is a man who captured images, wrangled authors, and corrected grammar. **Congratulations and thank you to Bill Litant,** Communications Director, Aeronautics and Astronautics Department.

– Department Head Jaime Peraire and the AeroAstro production team