AERO ASTRO

annual 2009-2010

ENVIRONMENT & ENERGY ISSUE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AEROASTRO

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AeroAstro is published annually by the Massachusetts Institute of Technology Department of Aeronautics and Astronautics, 37-395, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA. http://www.mit.aero

AeroAstro No. 7, December 2010

DESIGN

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Cover: Professor Mark Drela and AeroAstro seniors Nina Siu and Michael Lieu prepare a model of the D-8 aircraft for testing in MIT's Wright Brothers Wind Tunnel. Created by an MIT-led team, the D-8 is designed to use 70 percent less fuel than current planes, and reduce noise and nitrogen oxide emissions. See article, p. 2. (William Litant/MIT photo.)

Welcome, once again, to our annual publication, *AeroAstro*, which offers a window into some of the exciting things happening in the MIT Aeronautics and Astronautics Department.

Much of this issue focuses on our work in the areas of environment and energy. AeroAstro research in these realms is so broad and deep that selecting which projects to present in this issue was a challenge. Department faculty and students are making advances in such areas as innovative light-weight materials; new aircraft and engine designs; scientific assessments of aviation's climate, air quality, and noise impacts; environmental-economic analysis of proposed federal and international policies; alternative fuels lifecycle analysis; aircraft operations for reduced emissions; space-based sensing of the Earth's atmosphere; systems-architecture for the Earth Observing System; novel wind-energy concepts; and computational tools for modeling carbon sequestration concepts. In pursuing these endeavors we benefit from our network of collaborators both within and outside MIT.

Of course, there are many other great things happening in the department in areas other than environment and energy. For example, on the academic side, you will read in this issue about our exciting new degree — 16-ENG — a flexible major featuring the rigor and technical depth of our traditional engineering degrees, but offering a more interdisciplinary engineering education.

In all respects, we are a healthy department; a strong, collaborative community, with a deep commitment to educational excellence and advancing the state-of-the-art in aerospace. We welcome you to contact us at any time to learn more about our research, our educational programs, our people, and our department.

Ian Waitz

Department Head

David Darmofal

Associate Department Head

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

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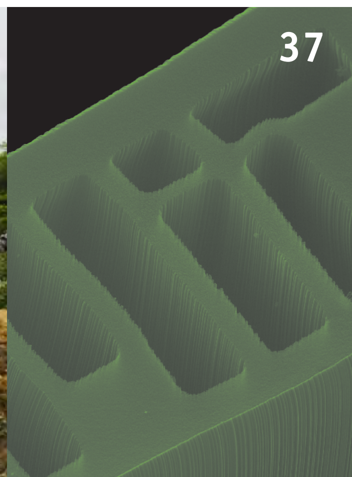
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MIT's designs for two future aircraft: the D Series (left), a double-bubble configuration, which is a 180-passenger plane, and the H Series, a blended-wing body which is a larger 350-passenger plane. Both would offer major fuel, noise, engine emissions, and runway length reductions compared to aircraft of today. (MIT/Aurora Flight Sciences image)

SUBSONIC CIVIL TRANSPORT AIRCRAFT FOR 2035

By Elena de la Rosa Blanco and Edward M. Greitzer

Aviation is a critical aspect of modern society, moving people and goods throughout the world and fostering economic growth. From 1981 to 2006, the demand for air transportation in North America grew by a factor of three; while forecasts for the next 25 years vary, they present a strong message that this trend will continue.

In 2008, NASA awarded four research contracts to define advanced concepts and enabling technologies for subsonic aircraft, in the 2035 timeframe, that could address the challenges posed by this increased demand. The research was part of the NASA N+3 program, where N+3 refers to aircraft three generations beyond those currently flying. The awards were to teams led by Boeing, Northrop Grumman, GE, and MIT. The MIT team, the only one led by a university, included Aurora Flight Sciences and Pratt & Whitney as partners. The collaboration among these three organizations resulted in the development of innovative conceptual designs, with the potential for step changes in capabilities, for future subsonic commercial transports.

PROJECT TARGETS: NOISE, EMISSIONS, FUEL, RUNWAY LENGTH

NASA set four targets as metrics for the design concepts: aircraft noise, engine emissions (as expressed in terms of nitrogen oxides produced during landing and takeoff), fuel burn, and runway length. The targets were aggressive; for example, a reduction of 70 percent in fuel burn for a reference aircraft and a noise goal comparable with that of the MIT-Cambridge University Silent Aircraft Initiative of several years ago, namely aircraft noise imperceptible beyond the airport perimeter. The team added a fifth metric as part of its design evaluation: the global average surface temperature change due to aircraft emissions, which reflects aviation's impact on climate change.

ADOPTION OF THESE DESIGNS COULD HAVE A MAJOR IMPACT ON FLEET-WIDE FUEL BURN, NOISE, EMISSIONS, CLIMATE, AND AIRPORT USE.

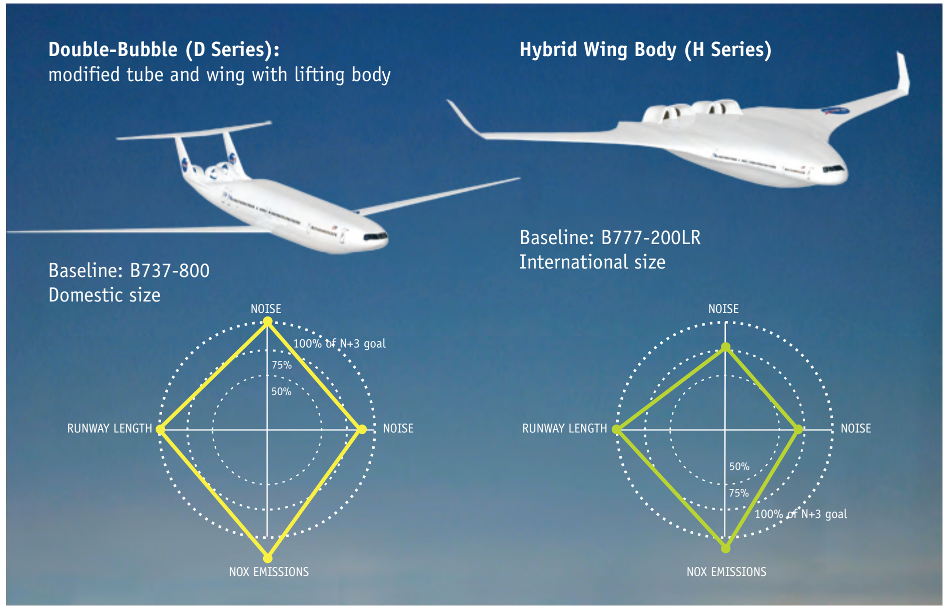
The multidisciplinary MIT-Aurora-P&W team had as an objective the rigorous definition of the potential for improvements in noise, emissions, fuel burn, climate, and airport use for subsonic transport aircraft. The project incorporated assessments of technologies in aerodynamics, propulsion, operations, and structures to ensure that a full spectrum of improvements was identified, plus a system-level approach to find integrated solutions that offer the best balance in performance enhancements. The assessment was enabled by a first-principles methodology that allowed simultaneous optimization of the airframe, propulsion system, and operations. The conceptual design exercise also included evaluations of the risks and contributions associated with each enabling technology, and roadmaps for the steps needed to develop the levels of technology required.

As the initial task — to frame the type of aircraft that would be most appropriate — the team defined a scenario for 2035 aviation based on estimates of passenger demand, airline operations, fuel constraints, airport availability, environmental impact, and other parameters. This scenario, plus the NASA targets, led to two conceptual aircraft designs. The missions of the two were selected from different market segments, but they were chosen so that, together, the two aircraft would represent a substantial fraction of the commercial fleet. This, in turn, implied that adoption of such designs could have a significant impact on fleet-wide fuel burn, noise, emissions, climate, and airport use.

DESIGNS FOR DIFFERENT MARKETS

A major result of the program was development of the two conceptual aircraft designs. One of these is aimed at the domestic market, flights from 500 nautical miles up to coast-to-coast across the United States. This design represents a 180-passenger aircraft, in the Boeing

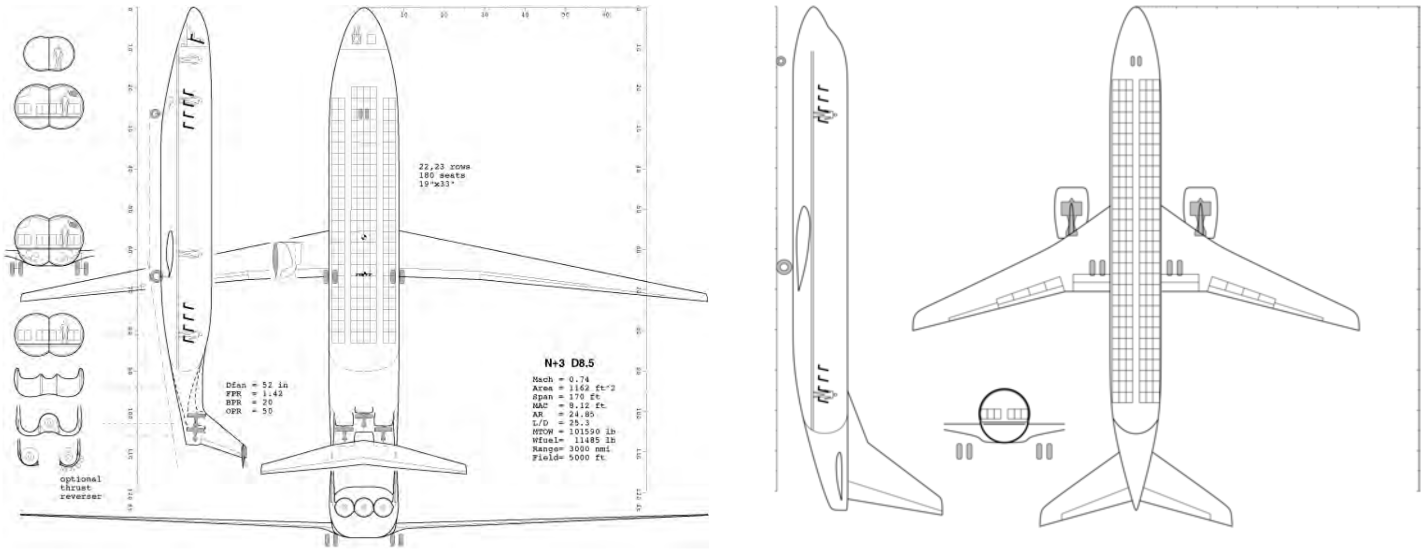
737 or Airbus A320 class, which makes up roughly a third of the current fleet. We named this concept the "D Series" because of its "double bubble" fuselage cross-section. The other aircraft, which we call the "H Series" for hybrid-wing-body, is defined for international routes. This latter design, envisioned as a Boeing 777 aircraft replacement, features a triangular hybrid wing body that blends into the wings, accommodation of 350 passengers in a multiclass configuration with cargo, and a range of at least 7,000 nautical miles.



Rendering and performance assessment of two MIT aircraft designs relative to the four N+3 NASA targets. The circles on the small graphs represent the 50 percent, 75 percent and 100 percent target levels targets, and the solid symbols indicate the performance of the concept aircraft.

The D Series configuration was calculated to meet fuel burn, engine emissions, and runway length targets, and to provide a substantial step towards achieving the noise target. The H Series was calculated to meet engine emissions and runway length targets, and is markedly improved compared to current aircraft for fuel burn and noise.

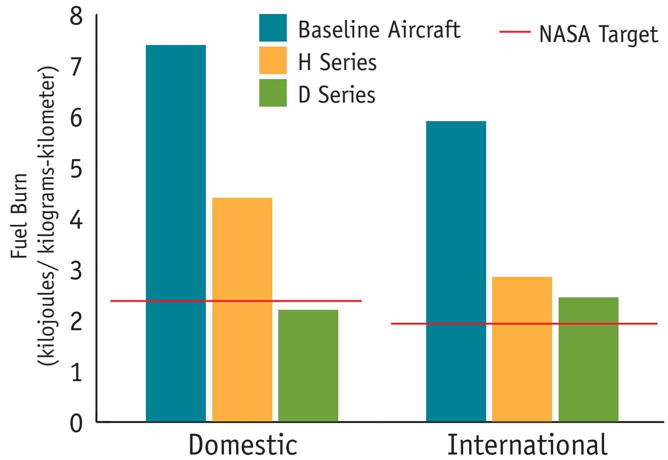
For both designs, the engines ingest the relatively slower moving air from the fuselage boundary layer (the air flowing next to the aircraft's body), providing a higher propulsive efficiency and, thus, an advantage from a fuel burn perspective. However, the flow into the engines consists of fluid from both within and outside of the boundary layer, so there is a non-uniform velocity into the engines. This is different from current engines, which hang in front of the wing and thus encounter virtually uniform flow. Integration of the aircraft and this unconventional propulsion system is one of the main technical challenges. The D Series flies about 10 percent slower than the 737, so the wings on the former, which have a much higher aspect, or length-to-width, ratio (29 vs. 10), require less sweepback than those on the latter. (The sweepback is to address deteriorations



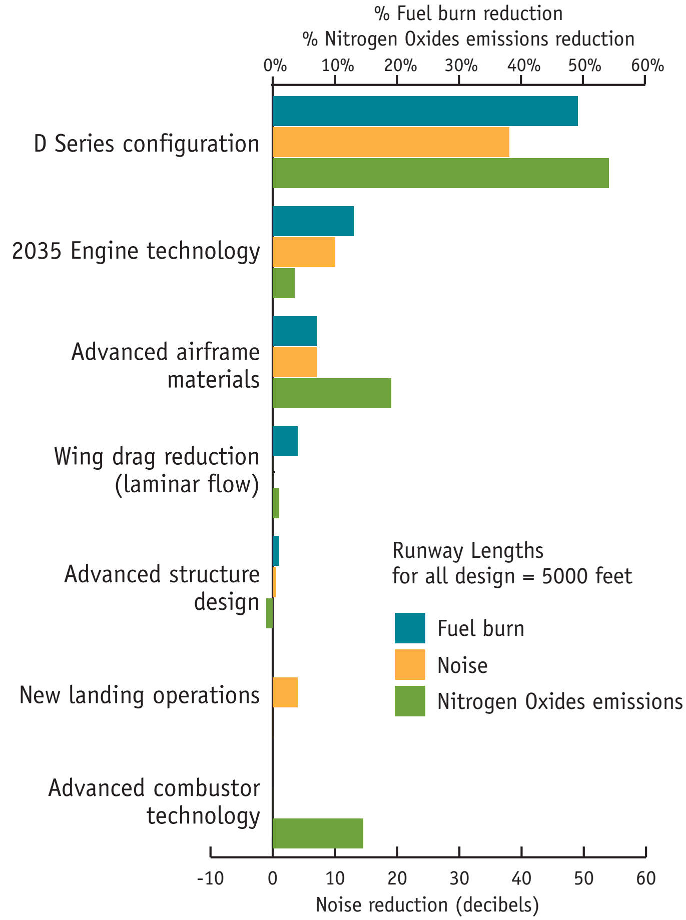
The D Series aircraft fuselage (left) is shorter and wider than that of a 737 (right). It provides three times the percentage of the overall lift on the aircraft, compared to that of the 737 fuselage (approximately 6 percent for 737).

in airfoil performance that can occur on an unswept wing at higher velocities.) The lower speed also allows other changes that result in a lighter, more efficient aircraft, leading to the 70 percent fuel burn reduction mentioned earlier.

The fuselage is shorter and wider than a 737's, and the D Series configuration gives numerous structural, aerodynamic, and propulsion system benefits, which contribute to the much reduced fuel burn. While both aircraft can be classed as "tube and wing," the D Series features two parallel tubes in a double-bubble fuselage cross-section accommodating two aisles, a possible time saver for passenger loading and unloading. The lifting fuselage allows smaller and lighter wings. The nose-up pitching moment from the upturned nose, and the twin vertical tails, reduce the size and weight of the horizontal tail. The D Series has



Performance of the D and H series aircraft compared with NASA N+3 targets



The D series configuration offers major performance benefits even with current technology. This chart shows the effect of configuration change on the NASA targets (the top three bars) compared with the benefits brought by changes in technology (the bars in all the other categories).

three engines placed above the aircraft between the vertical tails, shortening and lightening the landing gear and enabling smaller and lighter vertical tails. The configuration also provides acoustic shielding and, therefore, a reduction in the engine noise that propagates to the ground.

Compared to current aircraft, the double-bubble configuration offers a greater fuel reduction at the 737 payload and range than at higher payload missions. In contrast, the hybrid wing body achieves its best fuel burn at the 777 payload and range. Yet, even at the larger payload (and aircraft size), the double-bubble configuration offers essentially the same performance (NASA metrics) as the hybrid-wing body. Therefore, a second major finding is that although both configurations offer substantial benefits compared to the baselines, for the aircraft considered, the double-bubble configuration exhibits better performance (or equal performance for large payload/range) compared to the hybrid wing body.

A third result stems from our investigation of specific contributions to the performance of the D Series aircraft. The benefits of the N+3 concepts are from two sources. One is advances in specific technologies, such as stronger and lighter materials, higher efficiency engine components, and turbine materials with increased temperature capability. The other is the inherent benefit of the aircraft configuration. In other words, even limited to existing technologies (aluminum wings and fuselage, current technology engines with current bypass ratios, etc.), the configuration alone offers major performance benefits.

The step change in capability calculated for the D Series configuration is perhaps this project's most important finding. It implies that an aircraft configuration change has the potential to alter the face of commercial aviation, and that this change could occur on a much shorter time scale than required for maturation of many separate technologies. At this writing we await information on the second phase of the NASA N+3 program, under which we hope to take the next steps in bringing the D Series closer to service.

UNIVERSITY-INDUSTRY COLLABORATION

Two aspects of the university-industry collaboration are particularly important. The first was the virtually seamless interaction between the different organizations. The second, enabled by the first, was the emphasis on what is perhaps best described as the *primacy of ideas* rather than of organization or hierarchy. In other words, concepts and suggestions were considered directly on merit (e.g., content, strategic value, or impact) rather than the originator of the idea, or the legacy of the idea. From the start of the project, this was emphasized and fostered in team discussions. The consequence was that the team functioned with open-mindedness to new ideas and, as a direct corollary, a willingness to subject even cherished concepts to in-depth scrutiny. Our goal was to create a team in which "the whole was greater than the sum of the parts" because of strong interactions among participants. The achievement of this goal in an enterprise involving students, staff, faculty, and engineers in industry from a number of fields, with benefits to all parties involved, is also a major outcome of the project.

Team members

It cannot be emphasized too strongly that the project was a team effort, involving numerous MIT AeroAstro faculty and staff, as well as engineers from Aurora and Pratt & Whitney, taking major roles. MIT faculty and staff participants were Mark Drela, John Hansman, James Hileman, Jack Kerrebrock, Robert Liebeck, and Choon Tan. Jeremy Hollman and Wesley Lord were the team leads at Aurora Flight Sciences and Pratt & Whitney, respectively. The analyses and design information described came from all of these, from students Chris Dorbian, David Hall, Jonathan Lovegren, Pritesh Mody, Julio Pertuze, and Sho Sato, and from many others at Aurora and Pratt & Whitney.

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Edward Greitzer, the N+3 project principal investigator, is the H. N. Slater Professor of Aeronautics and Astronautics and former director of the Gas Turbine Laboratory. He is a Fellow of the ASME and AIAA, a member of the National Academy of Engineering, and an International Fellow of the Royal Academy of Engineering. He may be reached at greitzer@mit.edu.

An MIT team conducting research at Boston's Logan Airport is exploring how modifying ground operations could reduce aircraft fuel burn and engine emissions. Team members (from left) Tom Reynolds, Ioannis Simaiakis, John Hansman, Hamsa Balakrishnan, Harshad Khadilkar, and Diana Michalek use colored cards to suggest to air traffic controllers various rates at which they should allow aircraft to leave their gates. By optimizing this number, planes proceed efficiently with less time spent sitting on taxiways with engines running. (William Litant/MIT photo)

REDUCING AIRPORT SURFACE OPERATION ENVIRONMENTAL IMPACTS

By Hamsa Balakrishnan and R. John Hansman

Flight delays and aircraft taxiing contribute significantly to fuel burn and emissions. AeroAstro researchers are seeking ways to reduce these problems.

Greenhouse gas emissions are a significant and increasing concern for the aviation industry, which contributes 2-3 percent of total manmade emissions, and accounts for about 12 percent of the transportation sector's fuel burn and emissions. In 2007, the 7.4 million U.S. domestic passenger flights were responsible for 142.1 million metric tons of carbon dioxide emissions. Air traffic demand is rapidly increasing and there is growing regulatory and societal pressure to mitigate aircraft noise and emissions.

Air traffic delays have traditionally been the primary concern of the airline industry. In 2007, domestic air traffic delays in the United States cost airlines more than $19 billion and had an estimated $41 billion impact on the nation's economy. Recently, there has been much focus on passengers confined to aircraft during long taxi delays (more than 1,500 flights in 2007 had taxi-out times greater than three hours, although there were only about 600 such flights in 2009), resulting in new Department of Transportation policies such as the Three-hour Tarmac Delay Rule, by which aircraft that do not return to the gate after three hours on the tarmac can incur fines of $27,500 per delayed passenger. A frequently overlooked fact is that flight delays, in addition to inconveniencing passengers and airlines, have a significant environmental cost. Domestic delays in 2007 consumed 740 million gallons of jet fuel and released 7.1 billion kilograms of carbon dioxide into the atmosphere — about 5 percent of the

Visualizations of Boston Logan Airport surface surveillance data showing aircraft taxiing on the ground. Red icons denote arrivals and green icons denote departures. Researchers note the formation of queues at various locations on the surface, such as the aircraft waiting to cross an active runway on which an aircraft is coming in to land, and aircraft queuing by the side of the departure runway to await their turn to take off.

annual CO_2 emissions from domestic commercial aircraft. Because airborne delays are more expensive than ground delays, most delays (85 percent in 2007) occur on the ground. About 60 percent of the delays are at the gate before departure, while another 20 percent occur as aircraft are taxiing to the runway for takeoff.

TAXIING A MAJOR CONTRIBUTOR TO FUEL BURN, EMISSIONS

Taxiing aircraft contribute significantly to the fuel burn and emissions at airports. The quantities of fuel burned, as well as pollutants such as carbon dioxide, carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides, and particulate matter, are proportional to the taxi times of aircraft, in combination with other factors such as the throttle settings, number of engines that are powered, and pilot and airline decisions regarding engine shutdowns during delays. In 2007, aircraft in the United States spent more than 63 million minutes taxiing to their gates, and more than 150 million minutes taxiing out from their gates. And, the number of flights with lengthy taxi-out times (e.g., more than 40 minutes) has increased. The trends are similar at major European airports, where it is estimated that aircraft spend 10-30 percent of their flight time taxiing, and that a short/medium range Airbus A320 aircraft expends as much as 5-10 percent of its fuel on the ground.

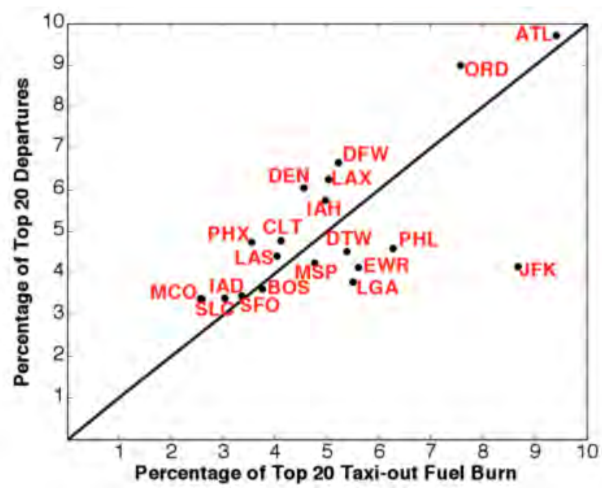
Domestic U.S. flights emit about 6 million metric tons of CO_2, 45,000 tons of CO, 8,000 tons of NO_x, and 4,000 tons of HC taxiing out for takeoff; almost half of these emissions are at the 20 most congested airports in the country. These pollutants contribute to low-altitude emissions, directly impact local nonattainment of air pollution standards, and represent a concern for human health and welfare. The severity of this problem varies from airport to airport, and is particularly acute in the congested New York area airports. Airport operational data analysis suggests that a significant portion of these emissions can be reduced through measures that limit airport surface congestion.

FUEL CONSERVATION ATTITUDES

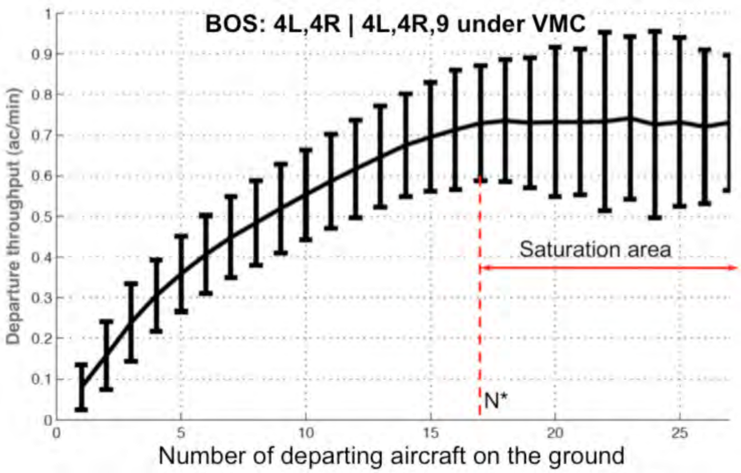
Given increasing fuel prices and concern about aviation-related environmental impacts, airlines have implemented practices to reduce fuel burn during ground operations. Such strategies include single-engine taxiing, minimizing aircraft auxiliary power unit use, controlling speed on the taxiway system, and holding aircraft at the gate during long delays.

Between August and December 2009, with the cooperation of the Massachusetts Port Authority, MIT AeroAstro researchers from the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), a nine-university research collaboration headquartered at MIT and sponsored by the FAA, surveyed airline pilots at Boston Logan International Airport to assess their attitudes towards fuel conservation during taxi operations and to document current fuel conservation practices, particularly single-engine taxi procedures.

This study found that the majority of pilots believe that fuel conservation is important; their motivation to conserve fuel is mainly driven by concerns about their airlines' economic viability, as well as the environmental impacts of aviation. The study also found that a majority of airlines appear to encourage single-engine taxi procedures as well as a variety of other fuel conservation measures. The survey found that single-engine taxi procedures were widely used on arrivals; 52 percent of pilots reported using them more than 75 percent of the time. They were infrequently used on departures; 54 percent of pilots reported using them less than 10 percent of the time. When pilots were asked whether they would be willing to wait at the gate if their position in



Plot depicting departure demand at the top 20 U.S. airports as a percentage of the total number of operations vs. the fuel burn as a percentage of the total departure taxi fuel burn.



Boston Logan Airport departure throughput as a function of the number of departures post-pushback. We note how the departure throughput initially increases, but saturates once the number of departures on the ground exceeds 17 aircraft. The vertical bars denote one standard deviation.

a takeoff queue could be guaranteed, a majority indicated a willingness to wait, suggesting that pushback control strategies, implemented correctly, have the potential to succeed in easing congestion and decreasing the environmental impacts of taxi operations.

REDUCING TAXI-OUT TIMES, FUEL BURN, EMISSIONS

At MIT, PARTNER is pursuing research on reducing taxi-out times, fuel burn, and emissions. The main motivation for our proposed approach to reduce taxi times is an observation of the performance of airport departure throughput. As more aircraft pushback from their gates onto the taxiway system, the throughput of the departure runway initially increases because more aircraft are available in the departure queue. However, as this number exceeds a threshold, the departure runway capacity becomes the limiting factor, and there is no additional increase in throughput. Any additional aircraft that pushback increase their taxi-out times, decrease the predictability of operations, and contribute to queues on the airport surface.

This phenomenon, in which the departure throughput saturates when the number of departures on the surface exceeds a threshold, is characteristic of congested airports, and suggests that limiting the buildup of queues on the airport surface by controlling the pushback times of aircraft could be a relatively simple way of decreasing taxi times and emissions. Using simulations of Logan Airport, we have estimated that if this policy were in effect during the most congested times of operation, flights during these periods would experience nearly a 20 percent decrease in taxi-out times. This benefit arises because flights taxiing during periods when the surface traffic exceeds this threshold experience long taxi times. Of course, there are practical challenges to overcome to achieve these benefits, such as the availability of gates, ATC workload, tug coordination, and passenger movement. Additionally, airline competitive factors such as on-time performance statistics, crew pay policies, and ground crew coordination pose significant challenges to surface movement optimization, and are being addressed in this project. As we go to press, we have just completed a reduced fuel burn and emissions demonstration at BOS, with the overall goal of initiating wider adoption of the methods throughout the United States. Early results from field tests, conducted between August 23 and September 23, 2010, show that during eight four-hour demonstration periods, more than 15,000 kg of fuel were saved, at the rate of 50-60 kg per gate-held flight. Moreover, these savings were achieved with average gate-hold times of only four minutes.

The problem of coordinating airport surface operations presents a range of exciting intellectual challenges that include understanding the cognitive processes of air traffic controllers, modeling the dynamics of various flows (both physical ones consisting of aircraft, as well as information flows between various components) using surface surveillance data, developing algorithms that determine the control strategies, and trading off the objectives and incentives of multiple stakeholders. But these challenges are accompanied by the wonderful opportunity to tackle some of the most critical problems being faced by air transportation today, and to significantly decrease the environmental impacts of airport operations.

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R. John Hansman is the T. Wilson Professor of Aeronautics & Astronautics and is the Director of the MIT International Center for Air Transportation. He conducts research in the application of information technology and systems analysis in operational aerospace systems. Hansman chairs the US Federal Aviation Administration Research & Development Advisory Committee, and has more than 5300 hours of pilot in command time in airplanes, helicopters, and sailplanes. He may be reached at rjhans@mit.edu

One of the defining challenges for the aerospace industry of the 21st century is understanding and reducing air travel's environmental impacts. With air travel demand forecast to triple by mid-century, meeting this challenge will require major advances in aerospace vehicle and information technology, changes to the design of our air transportation system, and the reshaping of our regulatory and policy frameworks. (Shutterstock image)

AVIATION AND THE ENVIRONMENT: WHICH WAY FORWARD?

By Steven R.H. Barrett and Ian A. Waitz

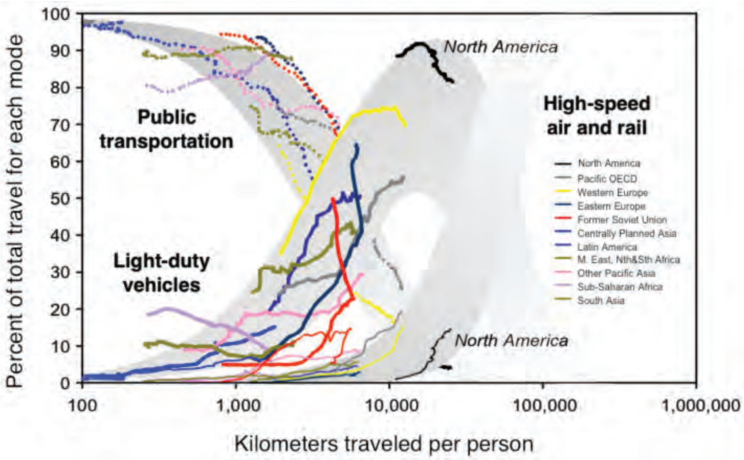
To achieve the right balance of options for mitigating aviation's environmental impacts — be these options technological, operational, or regulatory — we need to both understand the current impacts of aviation on the environment, and have the capability to estimate the effects of possible changes we make as the air transportation system evolves.

At MIT AeroAstro, we are addressing both problems. We are working to increase our fundamental understanding of the environmental impacts of aviation, and to develop tools that policy-makers and designers use to assess the environmental and economic implications of aviation policy and engineering decisions. Much of this work is done through the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), an FAA-NASA-Transport Canada-funded consortium of nine schools and 50 stakeholder organizations, led by MIT.

AVIATION IS DIFFERENT

Aviation is unlike other parts of the transportation sector. The travel chaos in Europe during the April 2010 Eyjafjallajökull eruption was a stark demonstration of aviation's societal and economic importance. No other mode of transportation enables such rapid movement of people and goods across countries and continents. Further, the opportunities for making technological and operational advances are often more limited than for ground-based systems because of the physical requirements for flight (e.g., lightweight, safety-critical systems).

Despite the speed of air transportation, the system as a whole has long time constants and considerable technological and organizational inertia. It can take 10 years to bring a new aircraft to market, aircraft stay in service for 25-30 years, and contemplation of major changes to the aviation system



Shift from public transportation to light-duty vehicles to high-speed transportation with increasing travel. Adapted from Schäfer (2006) and Schäfer, Heywood, Jacoby and Waitz (2009).

must be considered within the context of a safety-centric culture. Take the example of the Boeing 747; it was originally designed in the 1960s, but significantly more advanced versions of the aircraft will likely be in service beyond 2050. Further, aviation is intrinsically international, so effecting change typically requires a lengthy multilateral process.

By mid-century, air transportation is forecast to double or triple, with strongest growth in Asia. Indeed, growth in aviation has historically paralleled economic growth. Research tells us that as regions become economically more prosperous, the average miles traveled per person increases. But we also know that the average travel time "budget" per person per day is fixed at about 1.5 hours—this holds in developed countries, and it also holds in developing countries. Thus, as societies get richer they gradually transition to faster (and more energy intensive) modes of transportation. Ultimately, this means that given the economic means, billions more people will want to fly for day meetings a thousand miles away, and travel to different continents every year for vacation. Given these trends, it is no surprise that aviation is the fastest growing part of the transportation sector.

Finally, aviation pollutes at high altitude where it is the only significant source of anthropogenic pollution. This means that the way in which aviation impacts the environment is different. For example, aircraft contrails form and perturb our climate precisely as a result of where the emissions are deposited in the atmosphere. Much of our research is concerned with understanding how aviation impacts the environment, and how that impact can be reduced.

ADVANCING SCIENTIFIC UNDERSTANDING

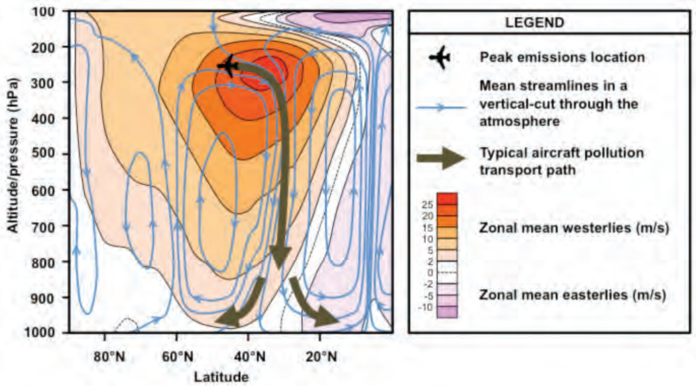
Can an aircraft flying at 35,000 ft cause a risk to the health of people on the ground? This question provides a useful example of the kinds of questions that we address with our research. For as long as aircraft emissions have been regulated, it has been assumed that only landing and takeoff (LTO) emissions—that is, emissions below 3000 ft above the ground—are of concern. But since

90 percent of aircraft fuel burn occurs at cruise, and lacking any rigorous justification of the 3000 ft cutoff, the question required a more careful assessment. This required a combination of aircraft emissions and atmospheric modeling, and making use of epidemiological evidence that enables us to relate pollutant concentrations to health risk.

Our findings were surprising. Aircraft emissions above 3000 ft cause perhaps five times more health impacts than emissions below 3000 ft—approximately 8000 or more premature deaths per year versus approximately 2000. To be clear, these are not big numbers compared to the total impacts of poor air quality, which the World Health Organization estimates to be about 1 million premature deaths each year (among many other adverse health impacts). Nonetheless, aviation impacts are significant and may outweigh the safety-related fatalities of the industry by an order of magnitude. Engine manufacturers currently design engines to minimize LTO emissions, which may not be right target.

We also found that aviation is the ultimate transboundary pollution source. It is an intercontinental pollution source, but all of our regulations and policies treat it as a local source. Aircraft emit most of their pollution at high altitude in the northern hemisphere, where the prevailing winds are strong and from the west, sometimes reaching 100 km/h. We calculated that while aircraft fuel burn in India and China combined accounts for about 10 percent of the global total, the two countries incur more than one-third of the health impacts of aircraft emissions. In other words, aircraft pollution from North America and Europe adversely impacts air quality in India and China. This is due to the prevailing winds at high altitude, the high population densities in India and China, and certain chemical properties of the atmosphere in that part of the world.

There are many uncertainties in analyses such as this. Apart from modeling uncertainties, there are uncertainties in the extent to which particles emitted from aircraft affect human health in the same way as particles emitted from other sources. This is still the subject of study. But despite the uncertainties, decisions have to be made; the world won't wait for perfect science. With this work, as with much of our other work, we are challenged to provide useful advice to decision-makers at the same time we are trying to better understand the underlying science.



The panel shows a vertical cut through the atmosphere. The longitude in the northern hemisphere is plotted on the abscissa with the North Pole on the left and the equator on the right. The ordinate of the panel is altitude (plotted as pressure in atmospheric modeling, where surface pressure is about 1000 hPa). An aircraft symbol depicts the location of peak emissions. The light blue lines show average streamlines (wind directions) on a vertical cut through the atmosphere. The polar, Ferrel and Hadley cells can be seen from left-to-right. A significant fraction of aircraft fly in the upper part of the Ferrel cell. Also shown in the panel is the mean zonal wind speed (i.e., wind speed from west to east) in red-white-purple. At typical cruise altitudes, the latitudes of peak aircraft emissions are in a region of strong westerlies, allowing for rapid transport of pollutants to the east. As pollution travels from west to east at high speed, it also descends towards ground level as depicted by the green line. This means that aircraft pollution in North America and Europe impacts surface air quality in Asia. Adapted from Barrett, Britter, and Waitz (2010).

MORE THAN JUST SCIENCE

It is a fact of life that the more we discover about how aviation impacts the environment, the harder policy and engineering decisions become. However, the aim is to help designers and policy makers make better decisions, not to make decision-making easier. Nonetheless, we do try to help in this regard by creating tools to enable policy-makers and engineers to assess the environmental and economic implications of their decisions.

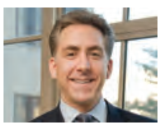
This is best illustrated with a contemporary example. The U.S. Federal Aviation Administration recently asked MIT AeroAstro for analyses to inform the U.S. position at the 2010 meeting of the International Civil Aviation Organization Committee on Environmental Protection, the main international aviation policy-setting body. The meeting focused on NO_x stringency, that is, the extent to which ICAO member states would introduce regulations to lower the maximum allowable NO_x emitted during landing and takeoff operations—a multi-billion dollar regulatory decision for an industry that historically operates in the red much of the time.

Design efforts to reduce engine NO_x emissions often result in tradeoffs—typically a small fuel burn penalty and an even smaller noise penalty. The fuel burn penalty leads to increased operating costs and thus increased ticket prices. In deciding whether or not to introduce regulations that further limit aircraft NO_x emissions, it is necessary to balance economic factors against climate, air quality and community noise impacts. This is made all the more challenging because of the range of environmental impacts. The CO_2 that comes with increased fuel burn has well known climate impacts, but the NO_x itself can both warm and cool the climate (depending on a variety of factors) and has a negative impact on surface air quality. While we can, and do, make estimates for all of these costs and environmental effects, there are important—even dominating—aspects of the decision that entail value judgments. For example, to what extent should we value climate impacts of CO_2 that may occur hundreds of years in the future, compared to premature mortalities that will occur in the next 10 years? Or, to what extent should we concern ourselves with noise-impacted communities around airports versus the traveling public, who often do not live in regions with high aircraft noise? Such issues require decisions to be made about the distribution of welfare — both in temporal and spatial dimensions. Sometimes our most important advisory role is in disentangling the parts of the decision that can be based on estimates of physical and economic quantities from the parts of the decision that require value judgments.

CONTRIBUTING TO AVIATION SUSTAINABILITY

These are only a few examples of our work on quantifying the environmental and economic impacts of aviation, and advising policy-makers. Other areas we are working on that are particularly focused on solutions that mitigate the environmental impacts of aviation include: analyzing the potential benefits of alternative aviation fuels and ultra-low sulfur fuels; assessing the environmental impacts of proposed redesigns of the U.S. air transportation system; and understanding the effects of including air transportation in a U.S. cap-and-trade system. In much of our work we are fortunate to collaborate with colleagues at the U.S. Federal Aviation Administration, other universities in PARTNER, and researchers overseas. Our broad collaborations and direct work with policy-makers will amplify our potential to contribute to developing a sustainable aviation system.

Steven R.H. Barrett is the Charles Stark Draper Assistant Professor of Aeronautics and Astronautics at MIT. His main research interest is in quantifying and mitigating the environmental impacts of aviation. He may be reached at sbarrett@mit.edu



Ian A. Waitz is the Jerome C. Hunsaker Professor and head of the MIT Aeronautics and Astronautics Department. He is director of the Partnership for AiR Transportation Noise and Emissions Reduction, a Fellow of the AIAA, and an MIT MacVicar Faculty Fellow. He may be reached at iaw@mit.edu

The unique nature of the space-based earth observation network that the Space Architecture Systems Group grad students (from left) Brandon Suarez and Daniel Selva, and Professor Ed Crawley are developing lies on its global coverage of the Earth. The system will offer an unprecedented ability to monitor climate, perform Earth science research, and forecast weather. (William Litant/MIT photo)

SPACE-BASED OBSERVATION PROGRAM IS KEY TO INFORMED CLIMATE CHANGE REMEDIATION

By Daniel Selva, Brandon H. Suarez, and Edward F. Crawley

MIT's Space System Architecture Group is architecting a complex system of weather balloons, aircraft, satellites, and a ground data network to monitor climate, perform Earth science research, and forecast weather for the United States.

With the threat of climate change on the horizon and generating more public debate than ever, an MIT Aeronautics and Astronautics research group is architecting a system to monitor climate, perform Earth science research, and forecast weather for the United States. The Earth observation system will comprise a complex network of satellites working in conjunction with aircraft, weather balloons, and other observation platforms. As government agencies like NASA and the National Oceanic and Atmospheric Administration look to the future, they will make decisions to build new satellites and invest in new technology. The MIT Space System's Architecture Group is creating the tools and methodologies to inform these decisions and create a holistic system.

DATA COLLECTION IS THE KEY TO CLIMATE CHANGE ACTION

There is now evidence that if governments around the world take no action to combat climate change, the consequences of the increase in anthropogenic greenhouse gas emissions are likely to harm ecosystems, human health, and the world economy. Most governments now understand that this is a real problem that requires a response. Reducing global greenhouse gas emissions, and investing in energy efficiency and renewable energy technologies can offset some of the climate change impact. Yet, mitigating and adapting to the impacts of climate change will require investments that could prove unaffordable for many nations. Therefore, it is crucial to make the right decisions; that is, the most effective decisions in terms of societal benefits and lifecycle costs.

A major factor undermining the decision-making process is the large uncertainty regarding both the economic and the scientific nature of the problem. Because of this, policy makers are reluctant to commit to action plans that could represent significant portions of their gross domestic products.

To resolve this uncertainty, scientists need long series of high temporal and spatial resolution data as inputs into their climate models. The only system capable of providing this data is a large, coordinated model that includes weather balloons, aircraft, satellites, and a ground data network for data sharing and distribution. Improved and continued space-based observations and measurements of the Earth's atmosphere, land, oceans and ecosystems are essential to this endeavor. The unique nature of space-based measurements lies in their global coverage of the Earth including the poles, the oceans, and non-populated land.

THE EARTH SCIENCE DECADAL SURVEY

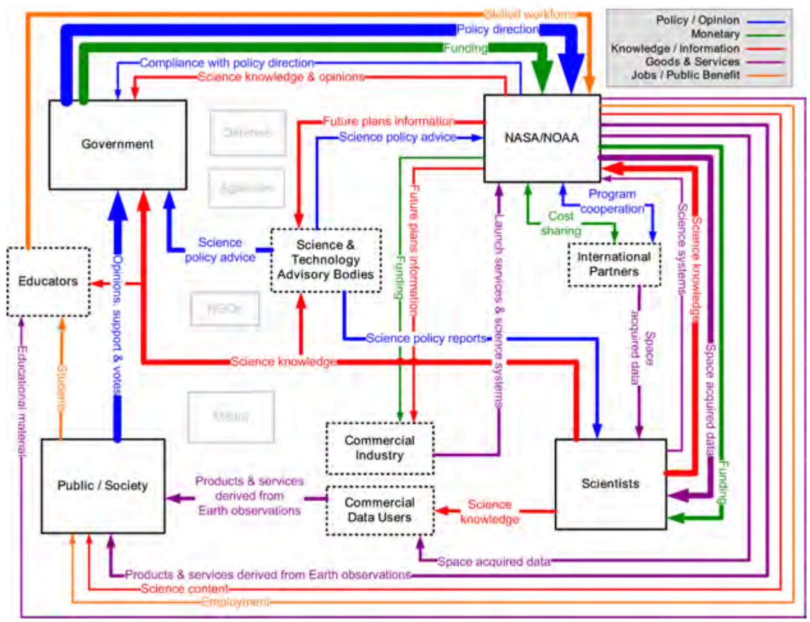
At no point in the history of the U.S. Earth science program has its value to society been clearer than now. However, under the current tight budgetary conditions, the problem of designing a space-based Earth observation program that satisfies the needs of all the Earth science communities and other stakeholders is, indeed, challenging. This is why NASA and NOAA commissioned the National Research Council to conduct the Decadal (10-year) Survey as a means to provide recommendations for the implementation of next decade's Earth observation program. In 2007, after three years of deliberation, the National Research Council published a report summarizing the conclusions reached by an ad hoc committee of experts. In addition to general guidance and high-level recommendations, the report provides a detailed baseline architecture for a program consisting of 38 instruments flown in 17 missions to be launched between 2010 and 2020.

The Decadal Survey baseline architecture was designed to satisfy the needs of all the Earth sciences disciplines under a set of assumptions. However, only three years after the NRC report's publication, many of the committee's assumptions are no longer valid. According to NASA sources and mission websites, mission cost estimates have grown, on average, by roughly a factor of two, while NASA's yearly budget has been almost halved. As a consequence, under current conditions, the baseline architecture would take almost four decades to launch. Furthermore, precursor missions that the committee assumed would be flown during the decade such as GPM, NPOESS, and OCO, have been delayed or even cancelled. It is obvious that alternative architectures need to be explored. The question we are asking is: can we do better than this baseline architecture under current assumptions?

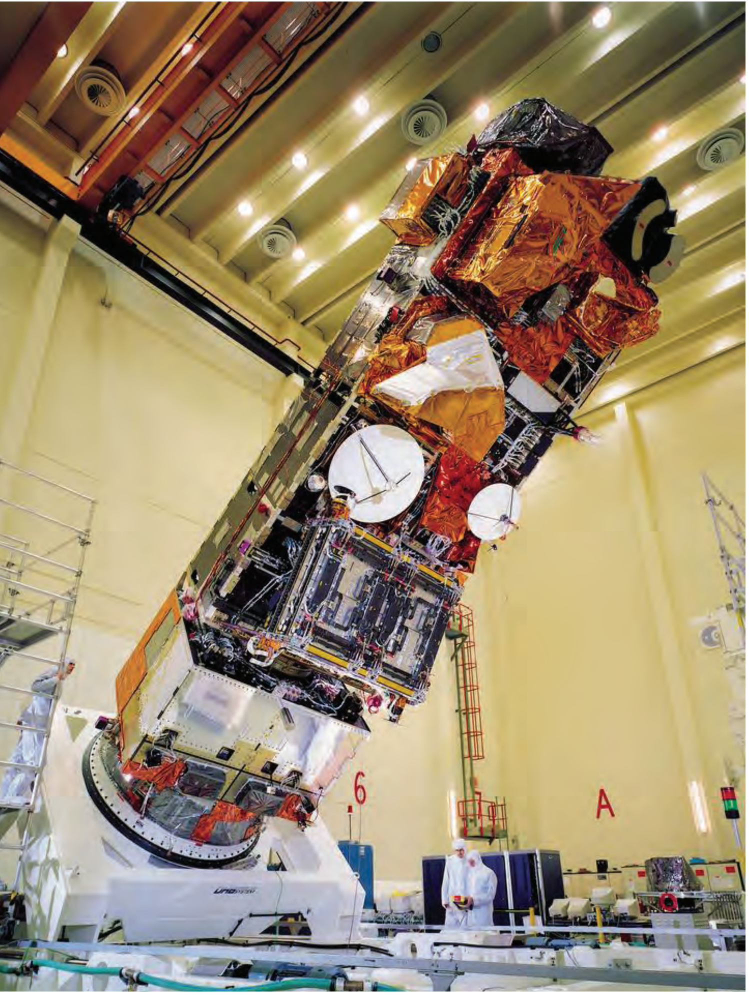
DEVELOPING STUDY METHODS AND TOOLS

For the last three years, we in the Space Systems Architecture Group have been developing a set of tools and methods that can help answer this question: stakeholder networks, campaign-level science traceability matrices, a mission scheduling algorithm, and an instrument packaging algorithm. These tools encompass a broad variety of disciplines including remote sensing, space systems engineering, engineering economics, project management, risk and reliability analysis, system design optimization under uncertainty, and artificial intelligence.

An outcome of a stakeholder analysis is a map in which all stakeholders—entities that put their assets at risk in the project—are represented as nodes and their relationships as arcs between these nodes. Based on the theory developed by Ed Crawley and Bruce Cameron (S.M. '07), and using data from a variety



The NASA-centric stakeholder map for the Earth Science program. Boxes represent stakeholders; textures indicate importance of the stakeholder to NASA. Arrows represent assets traded by stakeholders; arrow color indicates type of asset; thickness is proportional to strength of the link.

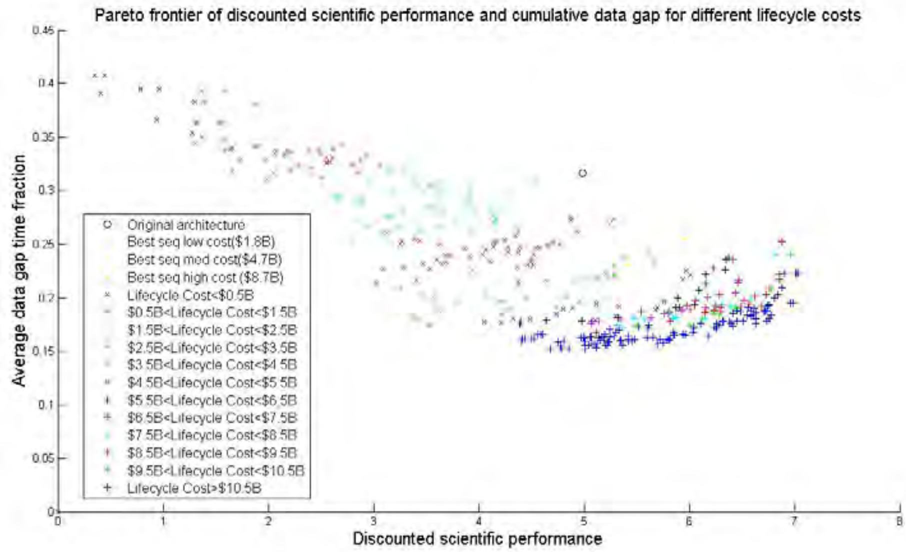


Launched in 2002, the European Space Agency's Envisat is the largest Earth observation satellite ever built. With 10 instruments and a mass of more than eight metric tons, it is expected to operate at least until 2013. This type of huge multi-instrument platform is of great use to scientists as it facilitates data cross-registration between instruments. However, multiple interferences among instruments made the development of this satellite an engineering nightmare. (NASA image)

of sources including newspapers and transcripts from the hearings in the House of Representatives, Tim Sutherland (S.M. '09) created the stakeholder map for the NASA Earth Observation Program, which contains dozens of stakeholders and hundreds of flows.

Thus, stakeholder analysis provides an assessment of the relative importance of different scientific disciplines represented by their corresponding "panels" in the Decadal Survey. The campaign-level science traceability matrix takes the output of the stakeholder analysis, a set of panel weights, and traces this value back into objectives, measurements, instruments and finally missions. Hence, this tool allows a systematic comparison of the relative importance of heterogeneous instruments and missions in the Decadal Survey. Based on careful reading of the NRC report and data from the NASA Goddard Space Flight Center, Theo Seher (S.M.'09) developed this simple and powerful tool, which has since been used to generate inputs for scheduling and packaging models.

The packaging tool takes a set of instruments as an input and explores different assignments of instruments into satellites. In other words, the tool compares architectures using small satellites carrying few instruments, with larger multi-instrument platforms. The flagship example of a large scientific observatory containing multiple instruments is the Envisat satellite. Because of scientific synergies among measurements, some of the instruments are great candidates for sharing a common satellite platform, thus achieving lifecycle cost reductions. Other instruments are less compatible for a variety of reasons such as electromagnetic, optical, mechanical, or thermal interference between instruments or very different technology maturity levels. All this is factored into this multidisciplinary tool developed by Ph.D. candidate Daniel Selva, which includes a complexity-based cost model, a schedule model based on Technology Readiness Levels, a risk model and a knowledge-based scientific model that embeds dozens of "synergy rules."



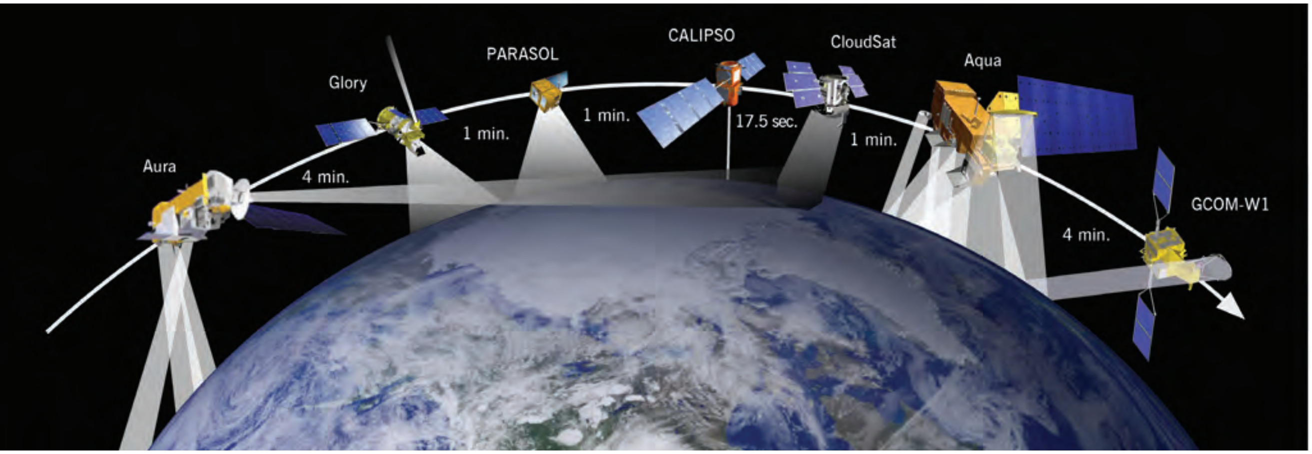
Set of non-dominated architectures found by the genetic algorithm when scientific performance (horizontal axis), data gap (vertical axis), and lifecycle cost (color) are all taken into account. In multi-objective optimization, an architecture is dominated if there exists another architecture that is better in all metrics simultaneously, i.e. in this particular example an architecture that provides higher scientific performance and closes more data gaps at a lower cost. The set of non-dominated architectures is usually called the Pareto frontier or the efficient frontier.

Finally, the scheduling tool orders the launches of the proposed satellites so that constraints for the estimated yearly budget allocated to NASA for Earth Science missions and earliest launch dates for each instrument are not violated. The scheduling tool is key to study the data continuity problem, since under tight budgets it will determine which measurements are guaranteed continuity and which are not. Brandon Suarez (M.S. '11) has developed a scheduling algorithm based on a multi-objective genetic algorithm that allows identification of architectures optimizing value delivery across disciplines and minimizing data gaps under different scenarios.

Tools like the ones we developed can help decision makers make the right decisions when architecting our space-based Earth observation program for the next decade, an essential component in the large system-of-systems that will provide the information that we need to design the policies that will combat global climate change.

ROOM FOR IMPROVEMENT

Results obtained with the packaging tool indicate that when taking into account current conditions, the baseline architecture can be improved. The image on this page shows hundreds of Pareto-optimal architectures evaluated in terms of lifecycle cost, scientific performance,



The NASA A-train. This kind of formation makes data cross-registration among instruments very easy while avoiding the engineering and programmatic issues of having many instruments on the same platform.

and their ability to close data gaps. In multi-objective optimization, a design or solution is dominated if there exists another design or solution that is better in all metrics considered, for example, in this case, an architecture that provides a higher scientific performance at a lower cost while closing more data gaps. Pareto-optimal architectures are those that are not dominated by any other. Our model finds that the baseline architecture is dominated. In other words, results indicate that similar performance can be achieved at lower cost by flying only a subset of the instruments in the baseline architecture in the right sequence.

Furthermore, even if we only consider the same set of missions, results obtained using both stakeholder analysis and the scheduling tool show that the sequence proposed in the NRC report is not the optimal one, given current budget and cost assumptions. Instead, the value delivered to society can be substantially improved by accelerating the GPS radio occultation mission and the three imaging synthetic aperture radar missions (SWOT, DESDYNI, SCLP). The reason is that these missions provide high value to a variety of scientific communities and also have large societal benefits (numerical weather prediction, disaster monitoring), as opposed to missions with a narrower scientific and societal scope.

The proposed launch date of some missions such as SMAP was found to be suboptimal when taking into account international partners. In this particular case, the European Space Agency launched SMOS in November 2009; it uses similar technology to measure the same physical parameter, although with lower spatial resolution. Our tools identified that there could be some benefit in delaying the launch of SMAP to gain experience from and provide data continuity after SMOS while investing in other missions with higher priority.

THE FUTURE OF SPACE-BASED EARTH OBSERVATION

Our studies are consistent with current findings indicating that distributed architectures composed of small dedicated satellites have great potential to fulfill program needs at reduced cost and risk, and improved responsiveness and flexibility. The scientific needs for simultaneity and coregistration of some measurements can be realized using architectures such as the NASA A-train where satellites with almost identical orbits follow each other with as little as 30 seconds of separation between them. Furthermore, recent advances in nanotechnology and control promise that very high-resolution images in many regions of the spectra can be obtained using swarms of nanosatellites flying in close formation. Many scientists, researchers, educators, and aerospace engineers are convinced that technologically, we are not as far as one would think from this dream. In the end, it is a matter of reversing the inertia of the system, as it is for climate change.

Daniel Selva, an AeroAstro doctoral candidate, holds degrees in electrical engineering and aeronautical engineering from UPC in Barcelona and Supaero in Toulouse. Between 2004 and 2008, he worked in French Guiana as a member of the Ariane 5 Launch Team. Selva's research focuses on system architecture and remote sensing satellite systems for Earth observation. He may be reached at dselva@mit.edu.

Brandon H. Suarez graduated from the AeroAstro department in 2009 and is working towards an M.S. degree. His graduate work is focused on the integration of aircraft and other non-space based observations into the Earth Observation System. Brandon also works for Aurora Flight Sciences in Cambridge, Massachusetts where he designs and builds small unmanned aerial systems. He may be reached at brandons@mit.edu

Edward Crawley is the director of the Bernard M. Gordon - MIT Engineering Leadership Program and a former head of the MIT Aeronautics and Astronautics Department. He is a Ford Professor of Engineering with appointments in Aeronautics and Astronautics, and Engineering Systems. His research focuses on the domain of architecture, design, and decision support in complex technical systems. He may be reached at crawley@mit.edu.

Complex computer flow models are a vital tool in tracking the interaction of pollutants with groundwater, such as in this area in proximity to a refuse site in Mexico. (Shutterstock image)

CONFRONTING ENERGY AND ENVIRONMENT'S TOUGHEST CHALLENGES WITH COMPUTATIONAL ENGINEERING

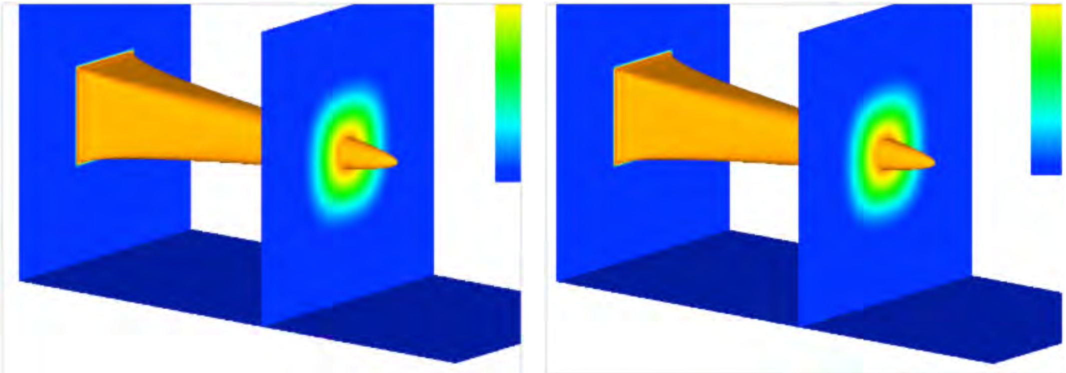
By Youssef M. Marzouk and Karen E. Willcox

Computational engineering has an essential role to play in addressing the energy and environmental challenges facing the next generation of aerospace systems.

At a basic level, computational modeling facilitates discovery by helping engineers and scientists develop a deeper understanding of physical processes. This understanding underpins a more fundamental approach to the design of novel aerospace systems, expedited by computational design tools.

Dramatic improvements in computer hardware and algorithms are generating opportunities for computational methods in a growing class of multidisciplinary problems. Computation now supports all aspects of the discovery and decision process: characterization of system properties, experimental design, prediction of system performance, and decision — design, planning, optimization and control. Each of these steps is key to meeting 21st century energy and environmental challenges.

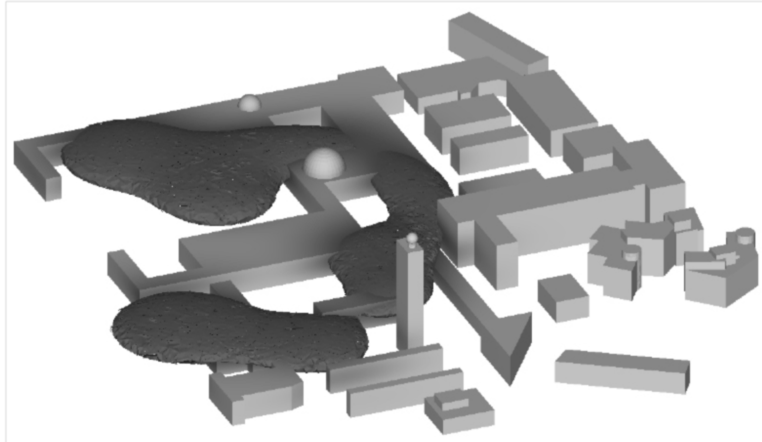
Prior to the modern computing era, discovery and decision were driven largely by a combination of ad hoc empirical modeling and experimentation. With the availability of supercomputing came the development of simulation-based analysis tools, such as computational fluid dynamics. As high performance computing moved from the supercomputer to the desktop, simulation-based analysis changed the face of aerospace design. Still, using simulation to drive discovery and decision remains out of reach for many large-scale and multidisciplinary systems. These are exactly the class of systems that describe the environmental impacts of aviation and the end-to-end costs of energy conversion. Realizing the benefits of computational engineering tools in this context represents a vital research frontier.



Reduced-order models are essential for reducing the computational time of reacting flow simulations for use in design and control applications. Here, a finite element model takes 13 hours CPU time to estimate the fuel concentration for a jet diffusion flame in a combustor (left). The reduced-order model (right) solves the same problem in a few seconds with high levels of accuracy. (D. Galbally, K. Fidkowski, K. Willcox, O. Ghattas image)

For example, *inverse problems* formalize the process of determining unobservable system properties through a fusion of experimental data and computational models. This process of data assimilation is central to performing predictive geophysical simulations. For example, a groundwater flow model requires estimates of the material properties of the earth subsurface, while climate and air quality models require estimates of global atmospheric properties. These systems are challenged by highly nonlinear physics and unknown parameter sets of high dimension, making solution of the inverse problem extremely difficult. *Experimental design* is key to guiding the collection of data, whether for control of combustor operating conditions at the aircraft system scale, or optimal deployment of mobile unmanned aerial vehicle sensors on a more global scale. In all of these cases, an outstanding challenge is the construction of scalable algorithms that can be executed in real time. Accurate *predictive modeling* of complex systems demands the inclusion of ever more disciplines (both engineering and socio-economic), more physics, and more scales — from elementary chemical reactions to global atmospheric dynamics. The *decision task* encapsulates all of these challenges and further requires computational models to be executed over a high-dimensional decision space, compounding the need for scalable and efficient algorithms and tools.

While these challenges may appear daunting in a deterministic setting, it is essential to note that uncertainty pervades almost every aspect of real-world discovery and decision. Uncertainty underlies the process of calibrating models from data: data are inevitably noisy, limited in number, and often indirect; model parameters and states may be impossible to fix under these conditions. Uncertainty also enters questions of optimal data collection — finding experimental designs that maximize information about selected parameters or states. And, uncertainty enters optimal design and decision — finding system configurations that are robust to variability and modeling error. Answering these questions requires that uncertainties be explicitly represented, propagated, and analyzed in our computational tools. Many external entities, such as the U.S. Department of Energy, recognize the crucial need for a shift away from deterministic modeling towards a paradigm that includes probabilistic information in all elements of the modeling and decision process. This shift requires new approaches for model formulation, model execution, statistical inference, and optimization under uncertainty.



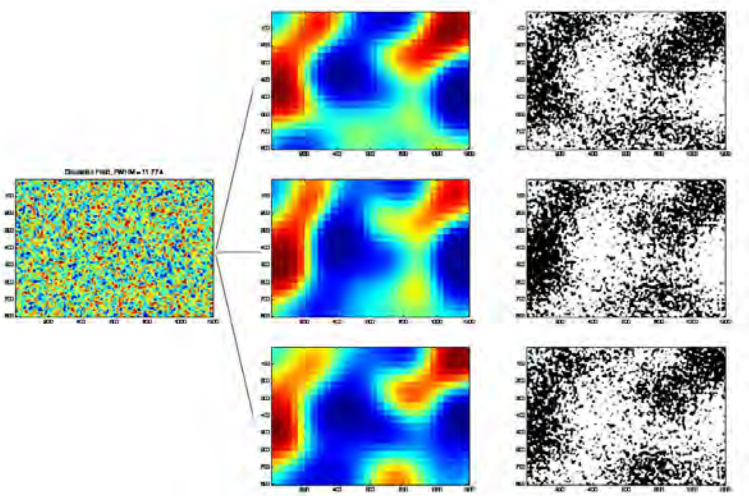
New computational methods are being developed to estimate physical properties from observational data. Here, the initial conditions of a contaminant release are estimated from synthetic measurements of contaminant concentration at sensor locations scattered throughout the MIT campus. (C. Lieberman, K. Fidkowski, K. Willcox, B. van Bloemen Waanders image)

FROM EXPERIMENTS TO MODELS

Computation plays an increasingly important role at the intersection of models and data. Researchers at the MIT Aerospace Computational Design Lab are developing new computational methods for estimating and refining physical models from observational data, for guiding data collection through optimal experimental design, and for using data to quantify the confidence that can be placed in model-based predictions.

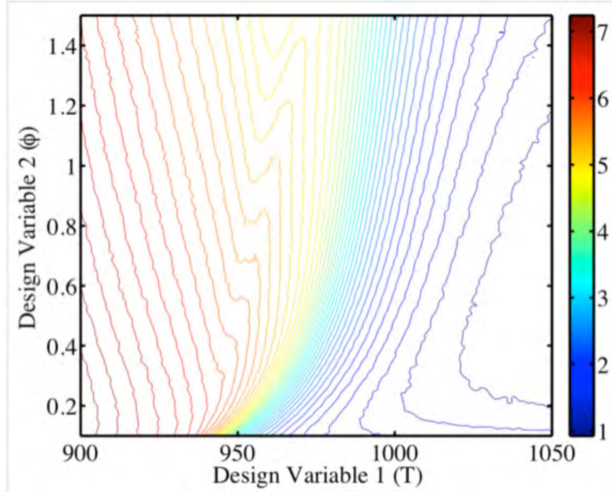
For example, predicting emissions from gas turbine combustors requires accurate chemical kinetic models to describe the development of nitrogen oxides, particulate matter, unburned hydrocarbons, and other pollutants. These kinetic models must retain predictive power over a range of temperature, pressure, and flow conditions, and often involve hundreds of elementary reactions. Uncertainties in the associated reaction rates and pathways can be quite significant: new engines and propulsion technologies may operate in low temperature or extreme pressure regimes where current kinetic models, even for widely-used fuels, much less alternative fuels, are not validated. And, the need for quantitative chemical and transport models is hardly limited to combustion. Kinetic models of adsorption, desorption, and reactions among surface species are fundamental to all aspects of electrochemical energy conversion. For example, characterizing the electrochemical oxidation of carbon monoxide and hydrogen on anode surfaces is critical to the design of fuel-flexible solid-oxide fuel cells.

To address these challenges, Aerospace Computational Design Laboratory researchers are developing systematic approaches to chemical kinetic modeling that fuse multiple sources of information, and that, crucially, take advantage of indirect data such as ignition delays and flame speeds for combustion kinetics, or impedance spectroscopy for reaction rates and transport phenomena in fuel cells. These methods cast model construction and refinement as problems of statistical inference, and thus provide data-driven assessments of the uncertainty in the models themselves. Realizing these methods involves computational challenges. Exploring model predictions over a range of parameter values may require thousands of repeated simulations, a computationally prohibitive undertaking for large-scale systems. Therefore, model reduction and output approximations are essential to the inference process. Simulation costs aside, simply exploring a high-dimensional parameter or model space with complicated correlation structure can present many difficulties. Our work encompasses dimensionality reduction and efficient sampling methods that make such sampling possible. For example, we have used dimensionality reduction and surrogate modeling to accelerate the inference of kinetic parameters and transport properties in chemically reacting flow by 2–3 orders of magnitude over conventional approaches.



Uncertainty is inevitable when learning from limited, noisy, and indirect data. Here, measurements of pressure and saturation are used to learn properties of porous media through which groundwater flows. Plausible realizations of the permeability field, at coarse and fine scales, are shown in each row. (S. Mckenna, Y. Marzouk, J. Ray, and B. van Bloemen Waanders image.)

A related effort aims to make data more informative, via optimal experimental design. Given limited experimental resources, it is critical to choose the best set of observations or experimental conditions with which to probe a system. Here, new computational tools can rigorously quantify the information value of an experiment with regard to particular parameters or performance metrics of interest, before the experiment is actually performed. Optimal experiments can then be chosen sequentially as part of the model construction process. For example, we have used optimal experimental design to choose mixture conditions in shock tube ignition experiments, to more efficiently learn chemical kinetic mechanisms for the combustion of alternative fuels.



Computation can be used to optimize the collection of experimental data by identifying the measurements that will be most informative about selected quantities of interest. Shown above are contours of expected information gain in the kinetic parameters of a hydrogen-oxygen system, resulting from a measurement of ignition delay. The axes of the figure describe the two design variables of the ignition experiment: T is the initial temperature and ϕ is the fuel-air equivalence ratio of the combustible mixture. (X. Huan, Y. Marzouk image)

TOWARDS SUSTAINABLE DECISIONS

As we work towards revolutionary improvements in aerospace systems' energy efficiency and environmental impact, computational engineering will play a key role guiding the design effort. In addition, future aerospace systems will incorporate unprecedented levels of automation to achieve environmental performance targets, requiring computational methods for real-time planning and control.

One area in which computational engineering is integral is the design of future aircraft to satisfy stringent environmental constraints on noise, air quality, and global emissions. These requirements necessitate the use of advanced technologies and novel configurations, which, in turn, demand high fidelity, physics-based design tools that do not rely heavily on empiricism and past experience.

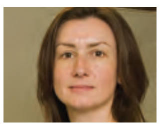
High-fidelity tools, such as computational fluid dynamics and finite element structural models, have become commonplace as analysis tools. However, a high-fidelity simulation-based design capability at the integrated aircraft system level remains out of reach. Aerospace Computational Design Lab researchers are tackling many aspects of this problem with a spectrum of research projects. These projects include developing the next generation of high-fidelity multiphysics simulation methods, computational geometry frameworks to support design, multifidelity and multidisciplinary design optimization methods, and adjoint methods for rapid computation of design sensitivities.

MIT is leading a team of researchers from Boeing, Stanford, and Purdue to develop advanced multidisciplinary optimization techniques for design of environmentally sensitive aircraft. A combination of advanced aerodynamic/structural/control concepts applied to the wing design enable dramatic improvements in fuel efficiency. The potential for significant drag reduction from extensive laminar flow and reduced span loading is well-known, yet structural penalties associated with increased span and with thin sections required of a low sweep transonic wing counter much of the aerodynamics gains. Active load control to reduce maneuver and gust loads can ameliorate some of these structural penalties. Achieving an aircraft design such as this — one that employs a high level of integration among disciplines, as well as a number of advanced technologies — challenges state-of-the-art design optimization methodologies. MIT researchers are developing methods to include disciplines not traditionally considered in early design. For example, our problem requires environmental models (noise, local emissions, and global emissions), as well as more detailed controls models (for load alleviation) than commonly appear in conceptual design. We have shown how mathematical strategies to decompose disciplinary components of the system are an effective way to achieve simultaneous optimization of the aircraft configuration and controller. The resulting design tool permits us to explore the optimal trades between increased wing aspect ratio and reduced loads, leading to aircraft designs with significant reductions in fuel burn.

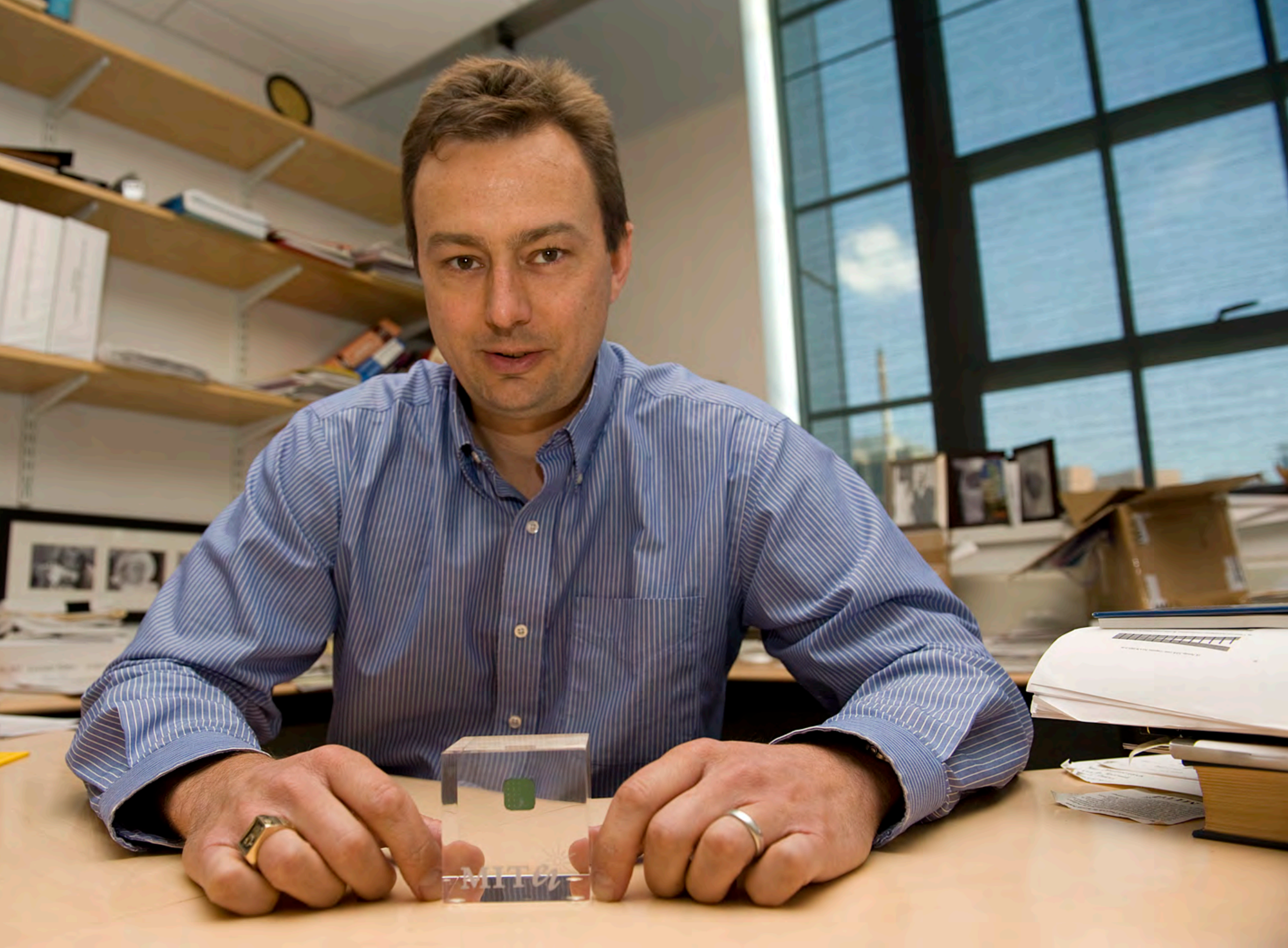
WE HAVE SHOWN HOW MATHEMATICAL STRATEGIES TO DECOMPOSE DISCIPLINARY COMPONENTS OF THE SYSTEM ARE AN EFFECTIVE WAY TO ACHIEVE SIMULTANEOUS OPTIMIZATION OF THE AIRCRAFT CONFIGURATION AND CONTROLLER. THE RESULTING DESIGN TOOL PERMITS US TO EXPLORE THE OPTIMAL TRADES BETWEEN INCREASED WING ASPECT RATIO AND REDUCED LOADS, LEADING TO AIRCRAFT DESIGNS WITH SIGNIFICANT REDUCTIONS IN FUEL BURN.

In addition to cutting-edge research, AeroAstro provides leadership in computational engineering across MIT. The interdepartmental master's program Computation for Design and Optimization and the MIT Center for Computational Engineering both have leadership roots in the department. Computational Engineering will also be among the first interdepartmental concentrations offered for the new 16-E flexible SB Eng degree. (See article by Darmofal and Waitz on p. 43 of this issue.) Through these and other initiatives, computational engineering at MIT is playing an ever-growing and vital role in developing the green technologies of today and tomorrow.

Youssef M. Marzouk is the Boeing Assistant Professor of Aeronautics and Astronautics at MIT. His research interests center on uncertainty quantification and data assimilation in complex physical systems, with an emphasis on chemically reacting flow in energy conversion processes, propulsion systems, and the environment. He received his S.B., S.M., and Ph.D. degrees in mechanical engineering from MIT, and spent four years at Sandia National Laboratories before joining the AeroAstro faculty in 2009. He can be reached at ymarz@mit.edu



Karen E. Willcox is an associate professor in the MIT Aeronautics and Astronautics Department. Originally from New Zealand, she has a bachelor of engineering (Hons.) from the University of Auckland, and S.M. and Ph.D. degrees from MIT. She has been on the faculty at MIT since 2001. Prior to that, she worked at Boeing with the Blended-Wing-Body design group. She may be reached at kwillcox@mit.edu



Professor Brian Wardle holds a plastic block in which is embedded a microchemical fuel cell developed in his lab. The device, designed for the Army as a replacement for batteries, was encapsulated and presented as a memento to the MIT Energy Initiative's founding board members. (William Litant/MIT photo)

ENERGY AND ENVIRONMENTAL FOCUS PERVADES AEROASTRO MATERIALS RESEARCH

By Brian L. Wardle

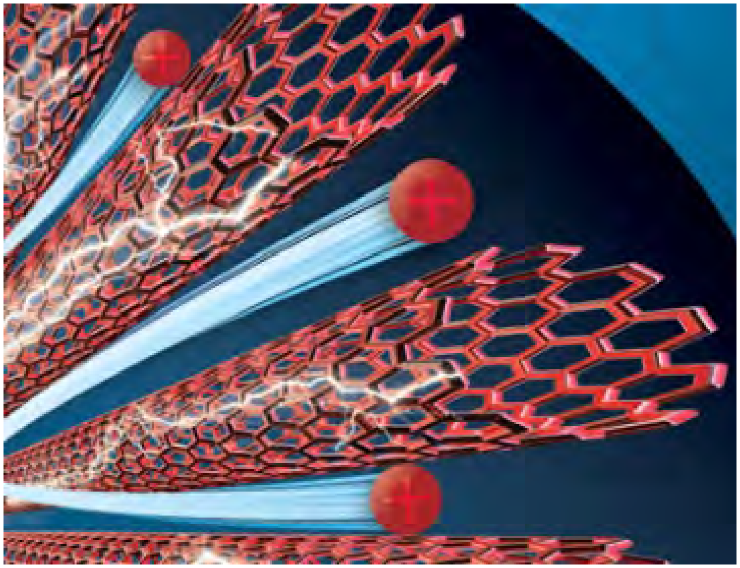
In 2005, MIT President Susan Hockfield announced her Institute-wide energy initiative, saying, “tackling the problems that energy and the environment present will require contributions from all our departments and schools …bringing scientists, engineers and social scientists together to envision the best energy policies for the future.”

While President Hockfield’s announcement marked an MIT-wide coordinated interdisciplinary energy-related research effort, a number of MIT researchers were already hard at work examining energy issues. Energy and environmental topics pervade much of the research done on the MIT campus, including that done by my research group.

At the time of the MIT Energy Initiative (MITEI) launch, I was the materials and structures lead for an Army-sponsored large multidisciplinary project focused on technologies to replace batteries: we were working on a miniature microchemical fuel cell built using ultra thin-films (1/1000 the thickness of a human hair) of materials. President Hockfield presented each of MITEI’s founding board members with a memento symbolic of the energy-related work MITEI would pursue. Each person was presented a display block in which was encapsulated a fuel cell fabricated by my student Namiko Yamamoto during her AeroAstro SM thesis. It is a very high-temperature (>600°C) micro-device using highly nontraditional (and nano-scale) materials that we designed, developed the processing to build, and then tested. Because the devices were built on a microelectronics/MEMS platform, thousands were created at one time, making it both scalable and a convenient gift item.

My active research includes several examples of energy and environment-related activities:

- **Green carbon nanotubes**: A key element in the majority of my current research involves a special arrangement of carbon atoms that create hollow graphitic tubes, or carbon nanotubes (CNTs). CNTs are the world's latest supermaterial, with many properties that exceed other known materials, and applications that range from microelectronics to space construction materials. Processes for growing CNTs are numerous, but all involve high temperatures and chemical reactions whose mechanisms are only partially understood. Many of the routes by which CNTs are manufactured involve dangerous and toxic inputs and byproducts. A key initiative led by recent MIT graduate and current visiting professor in my group, Dr. Desiree Plata, is to make the synthesis of CNTs more efficient and environmentally friendly. Professor Plata and I believe that keeping a focus on developing clean and responsible manufacturing is a key element for the long-term success of this important material. Related work in this area focuses on new catalyst seeds for growing the CNTs without using problematic metals, a new program sponsored by the National Science Foundation.



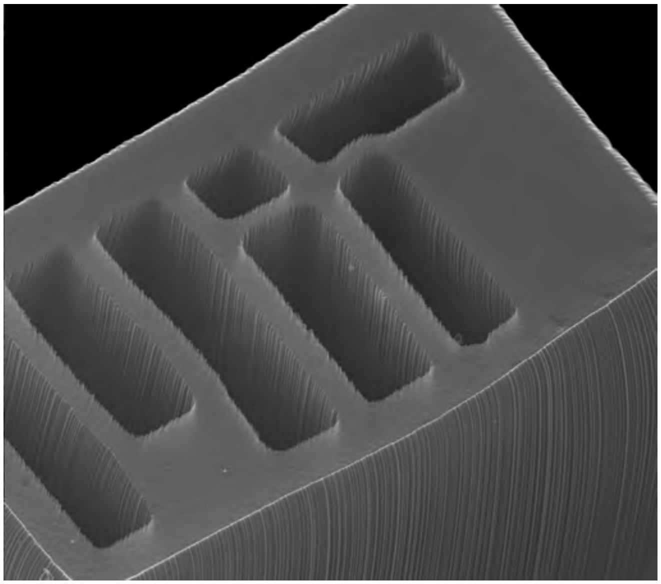
Ion-conducting polymer "expressways" are created between highly conductive aligned carbon nanotubes in the recently demonstrated hybrid electrodes for ionic actuators and energy harvesters. The "plus" ions are driven up and down the channels between the carbon nanotubes, which are filled with polymer, yielding near-optimal theoretical performance.

- **Materials for efficient transportation**: The core of my work is developing more advanced composites using nano-engineered materials for aerospace applications, work largely funded by industry through the Nano-Engineered Composite aerospace STructures (NECST) Consortium that I lead. Materials with advanced capabilities can directly reduce vehicle weight, and multifunctionality can replace dedicated systems with structures that can do more, such as self-sense for damage, and de-ice without heaters (e.g., where the composite structure serves as the heater). Much of the efficiency of new commercial composite aircraft comes from the use of traditional advanced composites and billions of dollars in lifetime cost savings is expected. Next-generation composites that NECST is developing would further enhance aircraft efficiency and what we learn may be transferable to other materials applications in transportation and building infrastructure.

WE ARE CONCERNED AND CONSCIOUS OF ENVIRONMENTAL HEALTH AND SAFETY CONCERNS AND PROPER PROCEDURES FOR WORKING WITH NANOMATERIALS IN A MANUFACTURING SETTING.

- **Environmental health of nanomaterials**: My group synthesizes and works with nanomaterials on a daily basis. We are concerned and conscious of environmental health and safety concerns and proper procedures for working with the materials in a laboratory setting. However, in understanding the issues for our work, we have found that the current state of understanding nanomaterials' health effects is nascent at best. We have opened our lab and processes to external researcher Professor Dhimiter Bello, from Occupational Hygiene and Work Environment Chemistry at UMass-Lowell, who, in collaboration with MIT's Environmental Health and Safety Office, is helping us better understand exposure. What we have learned has been shared through several nanoparticle exposure journal articles. We are posing questions such as: "what happens when you make a new material containing CNTs and then you need to do something simple like machine it?" Traditional tooling for composites is abrasive and creates a lot of dust. So, what is in the dust when carbon nanotubes are in the composites?

• **Pervasive energy for ubiquitous sensors**. Microdevice sensors, such as those that can be distributed over large areas for infrastructure monitoring and threat detection, need power, and neither solar nor batteries are practical due to desired lifetime and operational restrictions. A continuing effort in my research group is to use small mechanical vibrations to generate electrical power using piezoelectric materials. These vibrations are ubiquitous in the environment: they emanate from sources such as the wind, motion of people, and operation of machinery. Vibrations in cars and airplanes that are bothersome to passengers are power to be harvested. Piezoelectrics are intrinsically electromechanically coupled, and, therefore, can be used to power devices from these vibrations. We have focused on optimal design for power extraction and have built devices based on our models, which show that there are many applications where such energy harvesting is both practical and advantaged.



Aligned carbon nanotubes are organized as an MIT logo via photolithography and then grown in Wardle's lab. The aligned CNT "forest" appears optically and under scanning electron microscopy (as in the image) as black and solid, however, it is more than 99 percent air by volume. Aligned CNT forests like this are used in Wardle's energy storage and composite research.

• **Novel energy harvester electrodes**: Recently, my group collaborated to create the highest performing electrodes for a class of energy harvesters (and actuators) called ionic polymer actuators. We applied what we have learned from our work in composites and processing of nanomaterials, especially CNTs and polymers, and designed superior electrodes. In these devices, the limiting feature for efficiency and speed is how quickly ions move inside the electrodes. By creating aligned nanoscale channels between highly electrically conductive CNTs, we create "express lanes" for the ions to travel up and down. The devices can be run as energy harvesters or in the reverse as actuators, and have applications in harvesting energy from low-frequency high-amplitude sources such as waves in the ocean. This work is in collaboration with Professor Qiming Zhang's group at the Pennsylvania State University.

Some might think it a bit strange that a group from AeroAstro — in fact a group and a laboratory that works primarily on advanced materials and composites for aerospace applications — would contribute the energy souvenir for MITEI at its founding. However, this simply reflects the fact that in aerospace, energy efficiency has always been a critical concern.

Brian L. Wardle is an associate professor of aeronautics and astronautics at MIT where his work focuses on materials and structures. He pursues research in nano-engineered advanced composites, traditional composites, bulk nanostructured materials, power-MEMS devices (fuel cells and vibrational energy harvesters), and other structures and materials topics. Wardle is founder and director of MIT's Nano-Engineered Composite aerospace STructures Consortium. He is a principal member of the Technology Laboratory for Advanced Materials and Structures, and is active in the Microsystems Technology Laboratory and Materials Processing Center communities. He may be reached at wardle@mit.edu.

"With the new 16-ENG degree program, I have the opportunity to explore two great passions of mine, without which I would have had to choose one or the other. This degree's flexibility not only allows me to venture towards my desire to work with aerial vehicles, but also affords me the ability to pursue my interests in energy and alternative future energies."

- JASON ELIZALDE (LEFT)

"The new 16-ENG degree allows me to focus on my love for both aviation and space exploration. I'll be able to complement the core aerospace engineering program with courses pertaining to manned space flight and planetary sciences. It is my hope to use this tailored degree it to pursue my dream of one day becoming part of the history of manned space flight."

- EZEKIEL WILLETT

(William Litant/MIT photo)

NEW AEROASTRO 16-ENG DEGREE ADDRESSES GLOBAL CHALLENGES, INTERDISCIPLINARY STUDIES

by David L. Darmofal and Ian A. Waitz

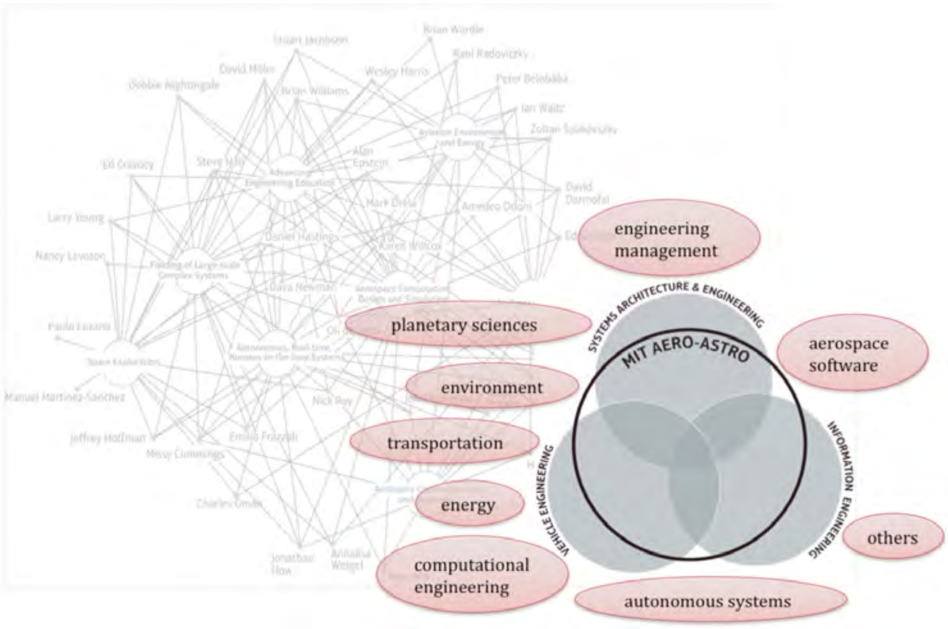
"Studying engineering at MIT can be a gateway to many things. MIT students are interested not only in a disciplinary engineering degree, but also in addressing broad and complex problems that affect the world, and we can help them by making an engineering degree more appealing and more suited to this wide range of application — while preserving depth and rigor that characterize an MIT education."

SUBRA SURESH, former dean of the MIT School of Engineering, now Director of the National Science Foundation

Our students have made it clear: while they are eager to learn the skills and gain the abilities of world-class engineers, many of them want to apply this knowledge to the critical global challenges of our age, including energy, transportation, climate change, and poverty. Others are interested in studying interdisciplinary fields such as computational, engineering management, and autonomous systems that can be applied in many engineering disciplines. The AeroAstro Department, the School of Engineering, and the MIT faculty heard them. This past April, the Institute gave AeroAstro a green light to proceed with an exciting new degree program: a flexible major option that still features our traditional aerospace engineering degrees' rigor and technical depth, but offers a more interdisciplinary engineering education.

NEW VISIONS IN ENGINEERING EDUCATION

In 1997, the Aeronautics and Astronautics Department developed a strategic plan that led to broadening our vision of aerospace engineering beyond the traditional aerospace disciplines



AeroAstro's strategic growth into systems architecture and engineering, and information engineering began around 1997. It led to an increased emphasis on interdisciplinary fields, such as computational engineering and engineering management, as well as multi-disciplinary fields such as energy and environmental studies. In the background is a connectivity map of the department's research thrusts and faculty.

of fluids, structures, propulsion, controls, and air and space vehicle design, to include the engineering of aerospace and related complex systems, and aerospace information engineering. We accompanied this with a significant reform of our pedagogy under the Conceive-Design-Implement-Operate context (http://www.cdio.org). Created by AeroAstro, CDIO, as the educational protocol is known, has since been adopted by 56 schools on six continents under the guidance of the MIT co-led CDIO Initiative international consortium, and is a foundation of the Gordon-MIT Engineering Leadership Program (http://web.mit.edu/gordonelp/), which provides leadership-oriented, discipline-building, hands-on engineering activities to nearly 90 undergraduates, the vast majority of whom are in the School of Engineering.

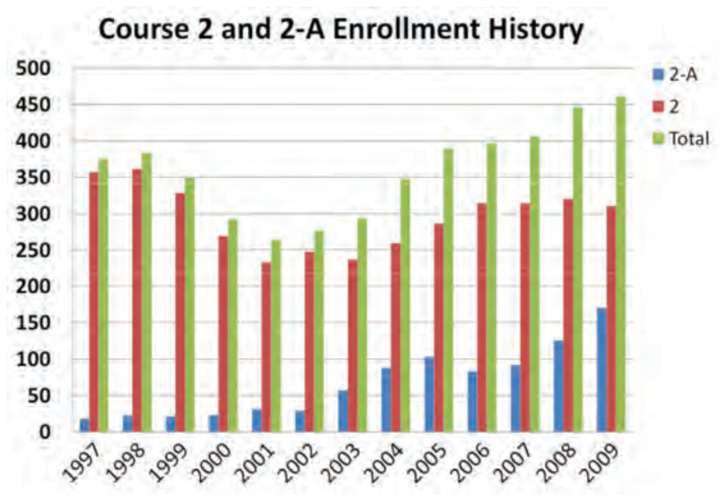
Since that time, aerospace engineering has continued to evolve; for example, the largest research areas in the department today are related to humans-in-loop autonomous systems, and energy/environmental matters associated with aviation.

This broadening of traditional engineering fields is not limited to aerospace engineering. National Academy of Engineering president and former MIT president Charles Vest says, "The last half of the 20th century was dominated by physics, electronics, high-speed communications, and high-speed long-distance transportation. It was an age of speed and power. The

21st century appears to be quite different, dominated by biology, structures, and information on a micro-scale, but also by macro-scale issues like energy, water, and sustainability." Vest adds, "Engineers will also face even larger challenges because the nation and world will need to call on them to seize opportunities and solve global problems of unprecedented scope and scale." With this breadth has come a blurring of boundaries among engineering disciplines, and between engineering and the physical and social sciences. Engineering graduates must be prepared for practice and research with broader interdisciplinary perspectives and greater understanding of the social, cultural, and political context of technological solutions.

Increased interest in multidisciplinary and interdisciplinary fields is also evident in recent surveys of MIT alumni and seniors. In the Class of 2005 Senior Survey, respondents indicated that effectively working on interdisciplinary engineering problems was important for their career plans (mean response of 5.9 out of 7, where 7=very important). However, this class was less positive about how its MIT engineering education had contributed to development of its interdisciplinary ability (mean response of 4.7 out of 7).

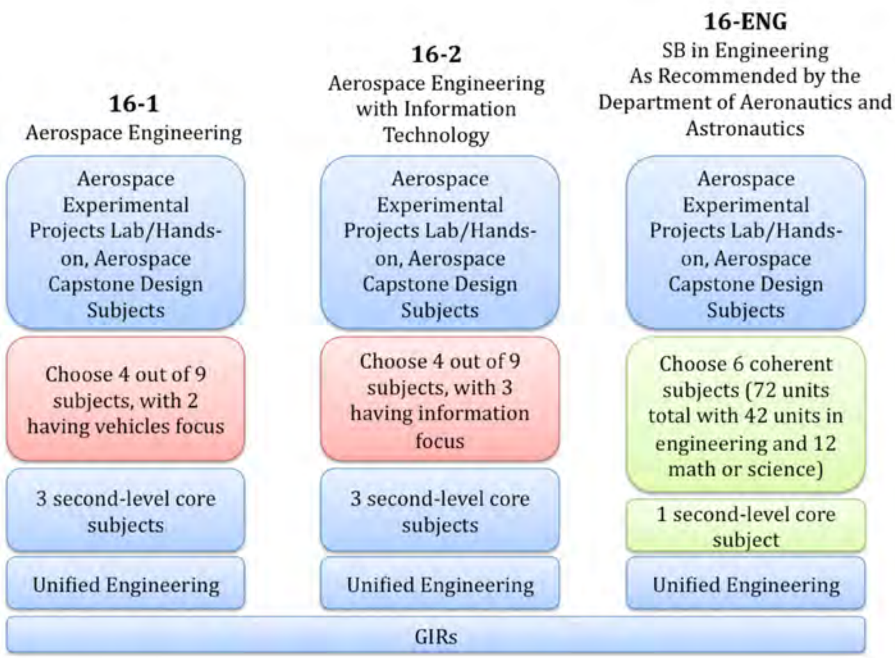
The rapid growth of the MIT Department of Mechanical Engineering's flexible undergraduate degree program, Course 2-A, offers more evidence of the demand for engineering degrees with increased multidisciplinary or interdisciplinary opportunities. The Course 2-A major is grounded in mechanical engineering fundamentals, but includes a concentration of six subjects to allow tailoring of an engineering degree to student interests. Students can design their concentrations, however, most choose pre-approved tracks that include: biomedical engineering; energy conversion engineering; engineering management; nano/micro engineering; sustainable development; control, instrumentation, and robotics. In fact,



Enrollment in Mechanical Engineering's Course 2 and 2-A degrees show rapid growth in Course 2-A since its 2002 ABET accreditation.

the Course 2-A degree has been offered since 1934, however, the rapid growth in enrollment only occurred after its 2002 ABET accreditation. In September 2010, the sophomore enrollment was more than 40 percent of the total sophomore enrollment in Mechanical Engineering.

To better understand the interest in awarding flexible engineering degrees in the MIT School of Engineering, seniors across the school were surveyed in 2009. Forty percent of the students expressed interest in such degrees, 30 percent were not interested, and 30 percent were not sure. Students who expressed an interest noted that it would expand their possibilities after graduation and would enable educational paths within MIT that are not possible now.



Comparison of AeroAstro's existing aerospace engineering degree programs (16-1 and 16-2) with the new flexible engineering degree program (16-ENG).

In 2007, a strategic planning effort lead by then Dean of Engineering Subra Suresh recommended developing flexible engineering degrees for students who wanted a multidisciplinary approach to their education without having to take additional classes on top of their already demanding course load. Suresh asked AeroAstro Department head Ian Waitz to lead a separate committee of six engineering department heads to explore this possibility. That committee unanimously proposed a schoolwide flexible degree program into which individual departments can choose to opt.

DESIGNING 16-ENG

During the 2009 fall semester, AeroAstro began discussing a flexible engineering degree. Given the inherent interdisciplinary and multidisciplinary aspects of aerospace engineering, the development of a flexible degree in our department was given strong support from the AeroAstro faculty as an effective means to allow our students to explore a wide range of aerospace-relevant topics by leveraging the wealth of subjects available throughout the Institute. Continuing a tradition of leadership in educational innovation, AeroAstro was the first department in the School of Engineering to proceed with the development a new flexible engineering degree under the Dean's schoolwide initiative.

Working closely with colleagues from Mechanical Engineering — department head Mary Boyce, department associate head for education John Lienhard, and associate professor Peko Hosoi — we developed a flexible degree program, Course 16-ENG, along the same lines as Course 2-A.

Our department's work began with developing a learning objective for students in the 16-ENG program, specifically: the 16-ENG learning objective is for the students to develop understanding and skill in addressing multidisciplinary and interdisciplinary aerospace engineering problems. This is accomplished through developing a strong foundation within aerospace engineering, and then

i also developing a greater understanding and skill in an interdisciplinary area relevant to aerospace engineering (e.g., energy, environment and sustainability, or transportation);

or

ii also developing a deeper level of understanding and skill in a field of engineering that is relevant to multiple disciplinary areas including aerospace engineering (e.g., autonomous systems, computational engineering, mechanics, or engineering management).

A set of predefined concentrations were developed for the 16-ENG rollout: autonomous systems, computational engineering, energy and environment, engineering management, and space exploration. We expect to develop additional concentrations in the coming years. As well, students have the option of developing their own concentration.

The 16-ENG curriculum is designed to offer flexibility within the context of aerospace engineering. This aerospace context is achieved in two ways:

- the inclusion of Unified Engineering, our integrative, foundational subject in aerospace disciplines

- the use of our existing aerospace laboratory and capstone subject sequences, which emphasize authentic project-based learning within the aerospace context, in multi-semester team environments with integral communications education

These are essential elements of the MIT AeroAstro educational program. They also combine well with any number of aerospace-related concentration areas. The technical depth of the concentration areas is ensured in part by a requirement that of the 72 units in the concentration, 42 must be engineering and 12 must be math/science. We are excited about the educational opportunities brought by this new degree. Undergraduate students who pursue 16-ENG will receive a more multi-disciplinary or interdisciplinary engineering education, but one that still features the rigor and technical depth of the department's traditional aerospace engineering degrees.

LAUNCHING 16-ENG

16-ENG received official approval from the Institute's faculty in April 2010. Since that approval, we have been busy implementing the degree program. We have been collaborating with colleagues around the Institute to develop cross-school (e.g., computational engineering) and cross-Institute (e.g., engineering management, space exploration) concentrations. We expect our first 16-ENG students to graduate in June 2012, as some students have already transferred to the new flexible degree.

In embracing AeroAstro's 16-ENG, School of Engineering associate dean for academic affairs, and current interim dean of engineering Cynthia Barnhart said, "This culture of multi-disciplinary research is one of MIT's great strengths, and the flexible degree programs are simply another expansion of this culture into education." Attaining the new degree will be a challenging and rigorous task befitting of the challenge of our existing aerospace engineering degrees. It fits well with the MIT tradition of preparing the individuals who will tackle the world's most important, timely, exciting, and difficult problems and do so with enthusiasm and unparalleled ability.

David L. Darmofal is a full professor and associate department head in the MIT Aeronautics and Astronautics Department. He is a member of the Aerospace Computational Design Laboratory. He is an Associate Fellow of the AIAA and an MIT MacVicar Faculty Fellow. He may be reached at darmofal@mit.edu

Ian A. Waitz is the Jerome C. Hunsaker Professor and department head in the MIT Aeronautics and Astronautics Department. He is director of the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER). He is a Fellow of the AIAA and an MIT MacVicar Faculty Fellow. He may be reached at iaw@mit.edu

AeroAstro alum and Aurora Flight Sciences president and CEO John Langford on the Kennedy Space Center's Shuttle runway. He'd considered basing a solar-powered aircraft at KSC that could stay aloft indefinitely to study stratospheric ozone.

ALUMNI INTERVIEW

JOHN LANGFORD BLENDS BUSINESS AND PASSION WITH UAVS AND ENVIRONMENTAL RESEARCH

by Dick Dahl

AeroAstro alumnus John Langford is the president and CEO of Aurora Flight Sciences Corp., a Virginia-based company that specializes in the design and construction of unmanned aircraft. Langford, who received his Ph.D. in aeronautics and public policy from MIT in 1987, was a member of MIT's Monarch and Daedalus teams, which designed and built record-setting human-powered aircraft in the 1980s.

Q. Could you describe the Daedalus Project?

Langford: I came back to MIT in the fall of '81 (from a job at Lockheed) for graduate school. While I was working on my master's, the British Aeronautical Society offered a prize called the Kremer Prize, to make a fast, human-powered airplane. "Fast" is a relative term. (Previous unmanned aircraft) had flown at about the speed you could walk. So we put a team together and did Monarch, and we actually won the prize. When that was done, we said, "Well, that was really cool." But everything about Monarch was a compromise for speed — for speed on the plane and speed on the project. Afterward, we were sitting around kicking back and forth the question, "How good could you make one of these?" Had it advanced to the point where you could re-create the myth of Daedalus?' We began to mention this publicly and, much to our surprise, instead of having a bunch of people scoffing, there were people around the department who thought this was pretty cool and encouraged us on. That became a three-year program that first did an airplane that was called the Michelob Light Eagle, because our first sponsor was Anheuser Busch, who underwrote the project with several hundred thousand dollars. We built the Eagle in '86 and in January of '87 we took it out to NASA Dryden (Flight Research Center in California) and it set five world records that still stand today. It still only went half the distance you'd have to go for the Daedalus flight (of 115 kilometers), but we proved that we could build an airplane with amazing performance. Based on that success, we got United Technologies to underwrite the actual construction of two Daedalus airplanes and in April of '88 we used one of those to fly from Crete up to Santorini and those records still stand today.

Q. How did Daedalus work?

Langford: A Greek Olympic cyclist by the name of Kanellos Kanellopoulos pedaled this thing using really good bicycle cranks that instead of driving a chain, drove a drive shaft through gear boxes to a very fancy propeller. It had the most amazing machine known to man—the human body—being applied in a different way. The human body is a great thinking machine, but it's not a great airplane engine. It was actually that experience of integrating unusual power sources into airplanes that is one of Aurora's fortes.

Q. Is that why you created Aurora?

Langford: Aurora was formed a year later with the idea of taking the technology that had come out of the Daedalus project and applying it to practical applications. The issue we first got directly involved in was stratospheric ozone. A team led by a scientist named Jim Anderson, who was a chemist at Harvard, put very sophisticated instruments on NASA's U2 and they flew it out of South America and down through the polar vortex and provided the data that were needed to make the positive diagnosis that it was CFCs that were triggering this catalytic cycle that was destroying ozone. The Harvard team was interested in finding ways to make these measurements more affordably and faster and safer.

I sent out a dozen letters to different people in industry and government that said we had this great student project; it said that we think if we took the technology of Daedalus—and at the time we were envisioning it as a solar-powered airplane—put thin solar cells on it, put some kind of energy-storage batteries or fuel cells in it so it can stay up overnight, you could have a platform that, unmanned, could stay up indefinitely. Of those 12 letters, only one person answered, and that was Jim Anderson, who said, "Sure, we think this is a great idea and we would love to collaborate with you on it." That was the genesis of Aurora.

It was a classic startup that took the few savings I had from my job at Lockheed, and that got us started in June of 1989 with two other Daedalus colleagues. We started in a little office in Alexandria, Virginia. And then Jim Anderson helped us get an "angel" investor who put in a couple hundred thousand dollars, and that helped launch the company and got us to the point where we began to win government contracts through the Small Business Innovative Research program, and one thing kind of led to another, and for the next five years for sure and almost through Aurora's first decade, we were focused exclusively on how you develop robotic airplanes for global-climate-change research.

Q. Your focus has changed since then?

Langford: Despite the fact that we were on a mission to save the world, it turned out to be very hard to get money to do that. We kept losing to companies that had military programs that basically paid all their overhead and R and D, so the economic viability of Aurora as a business that focused only on unmanned airplanes for global change was shaky, and it got shakier as the '90s progressed. By the late '90s we concluded that in order to prosper and survive as a business, we needed to move into the market where 98 percent of the money was, and that was the defense market. So we began to do that consciously—and then 9/11 happened, and the utilization of unmanned aircraft for military purposes has just gone exponential.

Q. How did your MIT education and experiences prepare you for your career?

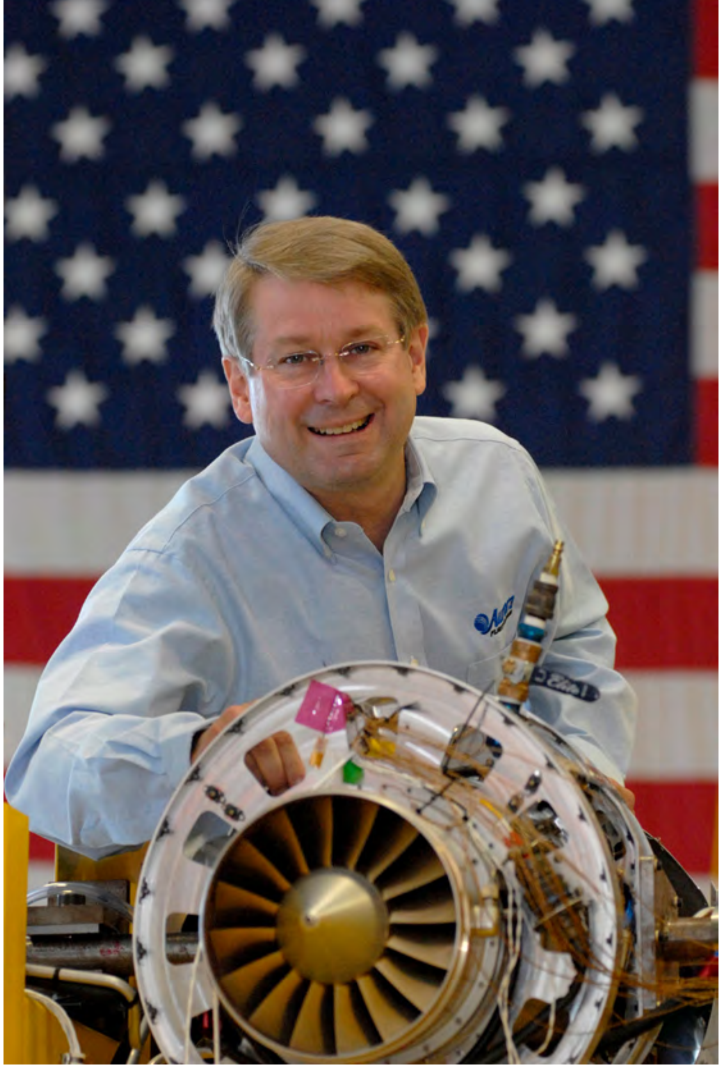
Langford: It's definitely the culture, but people create the culture. It's the people you meet, it's the inspiration, it's the challenges, it's the facilitization of being able to have a group of undergraduates be able to say, "Hey, let's go build an airplane," and, while it's not as though everything is just laid out for you, people were very helpful. Our first airplane was built in an old abandoned industrial building and the MIT real-estate office helped set us up in there.

Q. Do you have an ongoing connection with MIT?

Langford: Absolutely. For a long time after starting Aurora, a lot of us were able to stay in touch on the inertia of our previous contacts and relationships there. But about five years ago, we decided that we really needed to formalize and expand that. So we opened an office right in Cambridge, an R and D center, and today we have 35 or 40 people there working on a variety of projects, and almost every project we do has a university collaborator, and most of those are MIT. So either as official co-investigators or as consultants, we have a significant part of the AeroAstro Department involved formally now with Aurora.

Q. NASA granted $2.1-million to MIT for a project called "N+3" [See "Subsonic Civil Transport Aircraft for 2035" on page 1] involving Aurora and Pratt & Whitney, to design a future-generation commercial jetliner. Could you describe that?

Langford: NASA sent out a solicitation that said they wanted to study three generations of commercial air transport downstream. What would it look like and would it be possible to reduce the fuel consumption by 70 percent? We put a team together—Aurora, MIT, and Pratt & Whitney—and it turns out that what we thought



Langford with the Williams International turbojet that powers Aurora's Excalibur high-speed VTOL aircraft.

was an absolutely impossible goal when we started is actually possible. Seventy percent is not as crazy as it sounds. It's not easy, but you can in fact get a 40 or 50 percent reduction with a re-optimization of the whole system. This team has had a great first phase. This is all still study work, but of course what Aurora hopes will happen is that NASA will find our ideas compelling enough that we'll be able to build a demonstrator airplane. We're not proposing that MIT and Aurora start building commercial transports, but we do think that the team that we've got can build a demonstrator. That's exactly what Aurora does and is in business to do. It would be a sub-scale demonstrator, which in this case would still be a pretty big airplane that could demonstrate the technologies that could produce 40 to 70 percent reductions in fuel use in future commercial airliners. Then, at that point, you obviously need to team with one of the major primes that's in the commercial aircraft business.

Q. What projects are you working on now that are related to energy and environment?

Langford: The current issue we're focused on is the melting of the Greenland ice pack. What we're working to do is take Jim Anderson's instruments and one of our airplanes and equip it with special radar that can see through the ice and measure the thickness of the ice pack and basically map it on a detailed basis and track it over time to find out how quickly it's going to melt. This is not just an area of academic interest—this is what blows my mind. What really brought it home for me was when Jim Anderson showed me a map of Cambridge that he had developed to show to his own board, and it showed how much of Cambridge was under water if the global sea level rises one meter, three meters, seven meters. At seven meters, most of Harvard is under water. And if the ice pack all melts, it's seven meters. At three meters, MIT is gone. And we're not talking hundreds of years any more. There's evidence to support that it could happen in a century; there's even some evidence to suggest that it could be in the next 30 or 40 years. It's mind-boggling. And yet, the support is not there to even do the fundamental research. There's one little program here and one little program there. There's no systematic program to track and collect the measurements. And, it's still hard to get research money to investigate the state of the planet.

The U.S. government needs to re-focus its priorities for the issues that matter today. Unfortunately, it takes these cataclysmic events, like 9/11, to change these big bureaucracies. What we at Aurora want to see happen is that there has to be the same kind of focus on researching and measuring the environment that there is today on tracking terrorists. We've flown about 3 million flight hours with unmanned airplanes tracking terrorists because, in the post 9/11 world order, we are focused on individuals—where is a specific individual, what are they doing? We've developed the means to track them, and that's what robotic airplanes do. The utilization has gone from almost nothing to huge. But science flying is still about a thousand hours a year. It's a huge issue that this technology is here, but we have not found the national will to apply it, to take the measurements that we need to take, to figure out what the heck is going on with the environment. That's one of the great things about being back (working with) MIT. It's a way of pulling in the next generation of talent and enthusiasm to help us solve this problem.

Dick Dahl is a freelance writer who lives in Somerville, MA. He may be reached at rcdahl16@gmail.com.

LAB REPORT:

A 2009-10 Review of Aeronautics and Astronautics Department Laboratories

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

In AeroAstro's Neumann Hangar, master's candidate Sydney Do, assisted by Undergraduate Research Opportunities Program students Adrian Dobson (center) and Daniel Goodman, prepare Do's experimental airbag system that could cushion astronauts landing in the Orion spacecraft. (William Litant/MIT photo)

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

The Aerospace Computational Design Laboratory's mission is the advancement and application of computational engineering for aerospace system design and optimization. ACDL researches topics in advanced computational fluid dynamics and reacting flow, methods for uncertainty quantification and control, and simulation-based design techniques.

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

Uncertainty quantification and control is aimed at improving the efficiency and reliability of simulation-based analysis as well as supporting decision under uncertainty. Research is focused on error estimation, adaptive methods, ODEs/PDEs with random inputs, certification of computer simulations, and robust statistical frameworks for estimating and improving physical models from observational data.

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

ACDL faculty and staff include: Jaime Peraire (director), Doug Allaire, Marcelo Buffoni, David Darmofal, Mark Drela, Robert Haimes, Youssef Marzouk, Cuong Nguyen, QiQi Wang, and Karen Willcox.

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; estimation and navigation; sensor network design; and robust, adaptive, and nonlinear control. A key part 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, robust coordination algorithms for multiple helicopters, and vision-based sensing algorithms for indoor flight. Recent research includes the following:

Robust Planning: ACL developed a distributed task-planning algorithm that provides provably good conflict-free task allocations that are robust to poor network connectivity and inconsistencies in the situational awareness over the team. Recent work demonstrated key theoretical properties of this consensus-based bundle algorithm and extended the algorithm to enable tight linkages with a human operator.

Sensor Networks: ACL also addressed planning of mobile sensor networks (e.g., UAVs) to extract the maximal information from a complex dynamic environment such as a weather system. The primary challenge in this planning is the significant computational complexity due to the large size of the decision space and the cost of propagating the influence of sensing into the future. ACL developed a new set of methodologies that correctly and efficiently quantify the value of information in large information spaces, thus leading to a systematic architecture for planning information-gathering paths for mobile sensors in a dynamic environment.

Approximate Dynamic Programming: Markov Decision Processes are a natural framework for formulating many of the decision problems of interest to ACL, but the curse of dimensionality prevents the exact solution of problems of practical size. ACL has developed new approximate policy iteration algorithms that exploit flexible, kernel-based cost approximation architectures to quickly compute an approximate policy by minimizing the error incurred in solving Bellman's equation over a set of sample states. Experimental results demonstrating the applicability of this approach to several applications, including a multi-UAV coordination and planning problem.

Autonomous Vehicles: Working with Professor Emilio Frazzoli's lab as part of the Agile Robotics for Logistics program, ACL has developed a planning and control framework capable of autonomous forklift operations in an unstructured, outdoor warehouse setting. The framework implemented uses closed-loop rapidly-exploring random trees for navigation, and a steering controller coupled with pallet and truck perception filters for manipulation of pallet loads. In a presentation at Fort Belvoir, VA in June 2009, the team's robotic forklift demonstrated robust path planning capabilities in a complex environment with uncertain terrain, dynamic obstacles (including humans), and unreliable GPS data.

ACL faculty are Jonathan How and Steven Hall.

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

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

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

The group is working on a wide range of projects in the area of data communication and networks with application to satellite, wireless, and optical networks. Over the past year, the group continued to work on a Department of Defense-funded project toward the design of highly robust telecommunication networks that can survive a massive disruption that may result from natural disasters or intentional attack. The project examines the impact of large scale, geographically correlated failures, on network survivability and design. In a related project, recently funded by the National Science Foundation, the group is studying survivability in layered networks; with the goal of preventing failures from propagating across layers.

The group also started work on a new Army MURI (Multidisciplinary University Research Initiative) project titled "MAASCOM : Modeling, Analysis, and Algorithms for Stochastic Control of Multi-Scale Networks." The project deals with control of communication networks at multiple time-scales; and is a collaboration among MIT, Ohio State University, University of Maryland, University of Illinois, Purdue University, and Cornell University.

CNRG's research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Eytan Modiano directs the Communications and Networking Research Group.

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

COMPLEX SYSTEMS RESEARCH LABORATORY

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

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

Nancy Leveson directs the Complex Systems Research Laboratory.

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

GAS TURBINE LABORATORY

The MIT Gas Turbine Laboratory has had a worldwide reputation for research and teaching at the forefront of gas turbine technology for more than 60 years. 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.

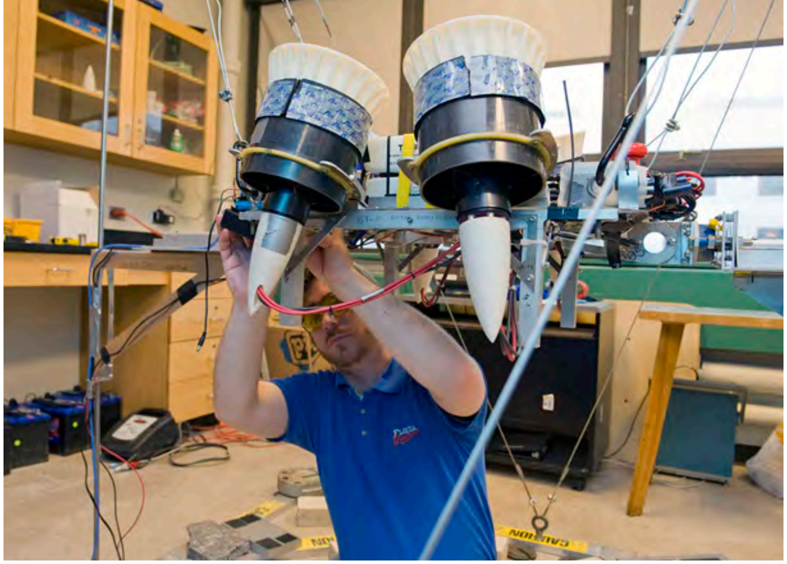
Examples of current and past research projects include: engine diagnostics and smart engines, aerodynamically induced compressor rotor whirl, a criterion for axial compressor hub-corner separation, axial and centrifugal compressor stability prediction, losses in centrifugal pumps, loss generation mechanisms in axial turbomachinery, the Silent Aircraft Initiative (a collaborative project with Cambridge University, Boeing, Rolls Royce, and other industrial partners), hybrid-wing-body airframe design and propulsion system integration for reduced environmental impact (NASA N+2), counter-rotating propfan aerodynamics and acoustics, an engine air-brake for quiet aircraft, inlet distortion noise prediction for embedded propulsion systems, novel aircraft concepts for 2035 (NASA N+3), high-speed micro gas bearings for MEMS turbomachinery, small gas turbines and energy concepts for portable power, and carbon-nano-tube bearings.

Zoltan Spakovszky is the GTL director. Faculty, research staff and frequent visitors include John Adamczyk, Nick Cumpsty, Elena de la Rosa Blanco, Mark Drela, Fredric Ehrich, Alan Epstein, Edward Greitzer, Gerald Guenette, Jim Hileman, Bob Liebeck, Jack Kerrebrock, Jürg Schiffmann, Choon Tan, and Ian Waitz.

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

HUMANS AND AUTOMATION LABORATORY

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



Phillip Cunio, an AeroAstro doctoral candidate, checks the Terrestrial Artificial Lunar and Reduced Gravity Simulator after a tethered flight. Cunio and his student colleagues are building the exploratory vehicle as a contender for the Google Lunar X-Prize. (William Litant/MIT photo)

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

Microgravity flight testing of a smart RFID-enabled Cargo Transfer Bag are AeroAstro graduate students Abe Grindle (left) and Howard Yue. Prof. Olivier de Weck is the project's principal investigator. (NASA photo)

flight deck automation and displays that are now in common use.

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

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

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems is an interdepartmental research laboratory that began in 1939 as the Servomechanisms Laboratory, focusing on guided missile control, radar, and flight trainer technology. Today, LIDS conducts theoretical studies in communication and control, and is committed to advancing the state of knowledge of technologically important areas such as atmospheric optical communications, and multivariable robust control. In addition to a full time staff of faculty, support personnel, and graduate assistants, scientists from around the globe visit LIDS to participate in its research program. AeroAstro/LIDS faculty includes Emilio Frazzoli, Jon How, Eytan Modiano, and Moe Win.

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

LEAN ADVANCEMENT INITIATIVE

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

LAI began in 1993 as the Lean Aircraft Initiative when leaders from the U.S. Air Force, MIT, labor unions, and defense aerospace businesses created a partnership to transform the U.S. aerospace industry using an operational philosophy known as "lean." LAI is now in its sixth phase and focuses on a holistic approach to transforming entire enterprises across a variety of industries. Through collaborative stakeholder engagement, along with the development and promulgation of knowledge, practices, and tools, LAI enables enterprises to effectively, efficiently, and reliably create value in complex and rapidly changing environments. Consortium members work collaboratively through the neutral LAI forum toward enterprise excellence, and the results are radical improvements, lifecycle cost savings, and increased stakeholder value. LAI's Educational Network, which provides LAI members with unmatched educational outreach and training capabilities, includes more than 50 educational institutions on five continents.

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

THE LEARNING LABORATORY

The AeroAstro Learning Laboratory, located in Building 33, is a world-class facility developed to promote 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.
- Two Project Offices — team-focused work and meeting spaces, which may be assigned to teams for weeks or months, or kept available as needed. These rooms support individual study, group design work, online work, and telecommunication.
- 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

In the AeroAstro Gelb Lab, students Christopher Jarrette and Evelyn Gomez assemble a student designed and built aircraft that will be used by the Air Force to test ground-based sensor systems. The project is part of a joint MIT-Lincoln Lab collaboration called "Beaverworks." (William Litant/MIT photo)

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 computerized 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, positioning him for convenient assistance.

Some of the projects undertaken by students in the Learning Lab during the past year include research into landing impact cushioning devices for re-entering manned spacecraft, design and construction of an aircraft for the AIAA Design/Build/Fly competition, construction of a D-8 aircraft wind tunnel model (see article, p.1), development work on the TALARIS planetary hopper, construction and testing of an autonomous robotic forklift, and design and construction of an aircraft for the Air Force to use in testing ground-based sensor systems.

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory addresses human-vehicle 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, 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, on many parabolic flights, and developed experiments for the International Space Station.

MVL has four 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. Space projects focus on advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity, development of mathematical models of spatial disorientation accident analysis, 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 fatigue detection in locomotive engineers, and advanced helmet designs for brain protection in sports and against explosive blasts. The laboratory also collaborates with the Volpe Transportation Systems Center, and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

The laboratory's "Bioastronautics Journal Seminar" enrolled 18 graduate students. For the seventh year, MVL MIT Independent Activities Period activities included a popular course on Boeing 767 Systems and Automation and Aircraft Accident Investigation, co-taught with B N. Nield, Boeing's chief engineer for the 777.

MVL faculty include Charles Oman (director), Jeffrey Hoffman, Dava Newman, and Laurence Young. They teach subjects in human factors engineering, space systems engineering, space policy, flight simulation, space physiology, aerospace biomedical engineering, the physiology of human spatial orientation, and leadership. The MVL also serves as the office of the Director for the NSBRI-sponsored 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/

THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for AiR Transportation Noise and Emissions Reduction is an MIT-led FAA/NASA/Transport Canada-sponsored Center of Excellence. PARTNER 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 nine universities, three federal 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 policymakers 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's most recent reports emanating from MIT research are "Near-Term Feasibility of Alternative Jet Fuels" (with the RAND Corp.) "Aircraft Impacts on Local and Regional Air Quality in the United States," and "Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels." These may be downloaded at http://web.mit.edu/aeroastro/partner/reports.

PARTNER MIT personnel include Ian Waitz (director), James Hileman (associate director), Hamsa Balakrishnan, Steven Barrett, John Hansman, Thomas Reynolds, Karen Willcox, Malcolm Weiss, William Litant (communications director), Jennifer Leith (program coordinator), and 15-20 graduate students and post docs.

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

SPACE PROPULSION LABORATORY

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

Manuel Martinez-Sanchez directs the SPL research group. Paulo Lozano is the associate director.

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. 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

NASA administrator Charles F. Bolden Jr. tries his hand at "flying" a SPHERES microsatellite during a May 2010 visit to the Space Systems Lab. (William Litant/MIT photo)

the International Space Station, and leading the Aero-Astro 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.

Major SSL initiatives study the development of formation flight technology. Significant research has been conducted using the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) facility, in the areas of distributed satellites systems, including telescope formation flight, docking, and reconfiguration. The SPHERES facility consists of three small satellites 20 centimeters in diameter that have flown inside the International Space Station since May 2006. They are used to test advanced control software in support of future space missions that require autonomous inspection, docking, assembly and precision formation flight. Over the past four years SSL has successfully completed 21 test sessions with eight astronauts. In 2009, SSL expanded the uses of SPHERES to include STEM outreach. In the fall of 2009 we began an exciting program called "Zero Robotics" to engage High School students in a competition aboard the ISS using SPHERES. In December 2010, 10 students from two Idaho schools came to MIT and saw their algorithms compete against each other in a live feed from the ISS. SSL plans to expand this competition to a national scale.

SSL is in the third year of the SEA program; the Space Engineering Academy immerses junior Air Force officers in the actual development of flight hardware providing first hand experience in implementing best (and avoiding worst) practices in space system procurement. It is a two year, end-to-end, flight-worthy satellite conceive, design, build, integrate, test, and operate program. The SEA students, together with several other SSL graduate assistants, formed a robust group of teaching assistants for the 16.83 capstone satellite design-build course. This year the course tackled two projects: the MIT Satellite team entry to the University Nanosatellite Program and conceptual design of the Exo-Planet cubesat to detect planets in other solar systems. The UNP entry, named CASTOR, is being developed jointly with the Space Propulsion Laboratory to demonstrate an innovative electric thruster. The propulsion system will be demonstrated in low Earth orbit with up to 1 km/s delta-V; if successful a 2 km/s delta-V spacecraft could be built to reach the moon! The Exo-Planet spacecraft is a cooperation between the SSL and faculty in EAPS and the Kavli Institute; it uses an innovative sensor with staged control to detect the presence of planets as they orbit around their stars.

The Electromagnetic Formation Flight testbed is a proof-of-concept demonstration for a formation flight system that has no consumables; a space-qualified version is under study. The MOST project completed architectural studies for lightweight segmented mirror space telescopes using active structural control. Multiple programs research the synthesis and analysis of architectural options for future manned and robotic exploration of the Earth-Moon-Mars system.

SSL continues to lead the development of methodologies and tools for space logistics. Jointly with Aurora Flight Sciences, SSL is developing prototypes for automated asset tracking and management systems for ISS based on radio frequency identification technology. Together with the Jet Propulsion Laboratory, SSL is editing a new AIAA Progress in Aeronautics and Astronautics Volume on Space Logistics that summarizes the current state of the art and future directions in the field.

2009-2010 SSL personnel included David W. Miller (director), John Keesee, Olivier de Weck, Jeffrey Hoffman, Edward F. Crawley, Daniel Hastings, Annalisa Weigel, Manuel Martinez-Sanchez, Paulo Lozano, Alvar Saenz-Otero, Paul Bauer (research specialist), SharonLeah Brown (administrator and outreach coordinator), Brían O'Conaill (fiscal officer), Marilyn E. Good (administrative assistant), and Deatrice Moore (financial assistant)

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

TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES

A dedicated and multidisciplinary group of researchers constitute the Technology Laboratory for Advanced Materials and Structures. They work cooperatively to advance the knowledge base and understanding that will help facilitate and accelerate 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. A significant initiative involves engineering materials systems at the nanoscale, particularly focusing on aligned carbon nanotubes as a constituent in new materials and structures. This initiative is in partnership with industry through the Nano-Engineered Composite aerospace STructures (NECST) Consortium founded at MIT in 2007. Thus, the research interests and ongoing work in the laboratory represent a diverse and growing set of areas and associations. Areas of interest include:

- nano-engineered hybrid advanced composite design, fabrication, and testing
- fundamental investigations of mechanical and transport properties of polymer nanocomposites
- characterization of carbon nanotube bulk engineering properties
- carbon nanotube synthesis and catalyst development
- 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. A recent addition includes several reactors for synthesizing carbon nanotubes. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility. TELAMS maintains capabilities for environmental conditioning, testing at low and high temperature, and in hostile and other controlled environments. There are facilities for nano and microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization.

With its linked and coordinated efforts, both internal and external, the laboratory continues its commitment to leadership in the advancement of the knowledge and capabilities of the 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. This commitment is exemplified in the newly formed NECST Consortium, an industry-supported center for developing hybrid advanced polymeric composites. In all these efforts, the laboratory and its members continue their extensive collaborations with industry, government organizations, other academic institutions, and other groups and faculty within the MIT community.

TELAMS faculty include Paul A. Lagacé (director), Brian L. Wardle, John Dugundji (emeritus), and visitors Antonio Miravete, Desiree Plata, Luis Rocha, and Junichiro Shiomi.

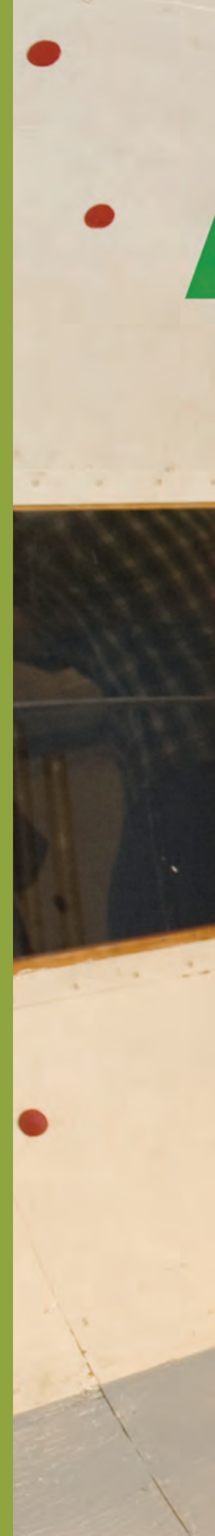
Visit the Technology Laboratory for Advanced Materials and Structures at http://web.mit.edu/telams/ and the Nano-Engineered Composite aerospace STructures Consortium at http://necst.mit.edu

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.

Lab director Moe Win and a team of undergraduate and graduate students competed in the Institute of Soldier Nanotechnologies Soldier Design Competition. In this contest they demonstrated the first cooperative location-aware network for GPS-denied environments, using ultra-wideband technology, leading to the team winning the L3 Communications Prize. They are now advancing the localization algorithms in terms of scalability, robustness to failure, and tracking accuracy.

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.

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

WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

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